Computations of Aerodynamic Performance Databases using Output-Based Refinement

Marian Nemec and Michael J. Aftosmis

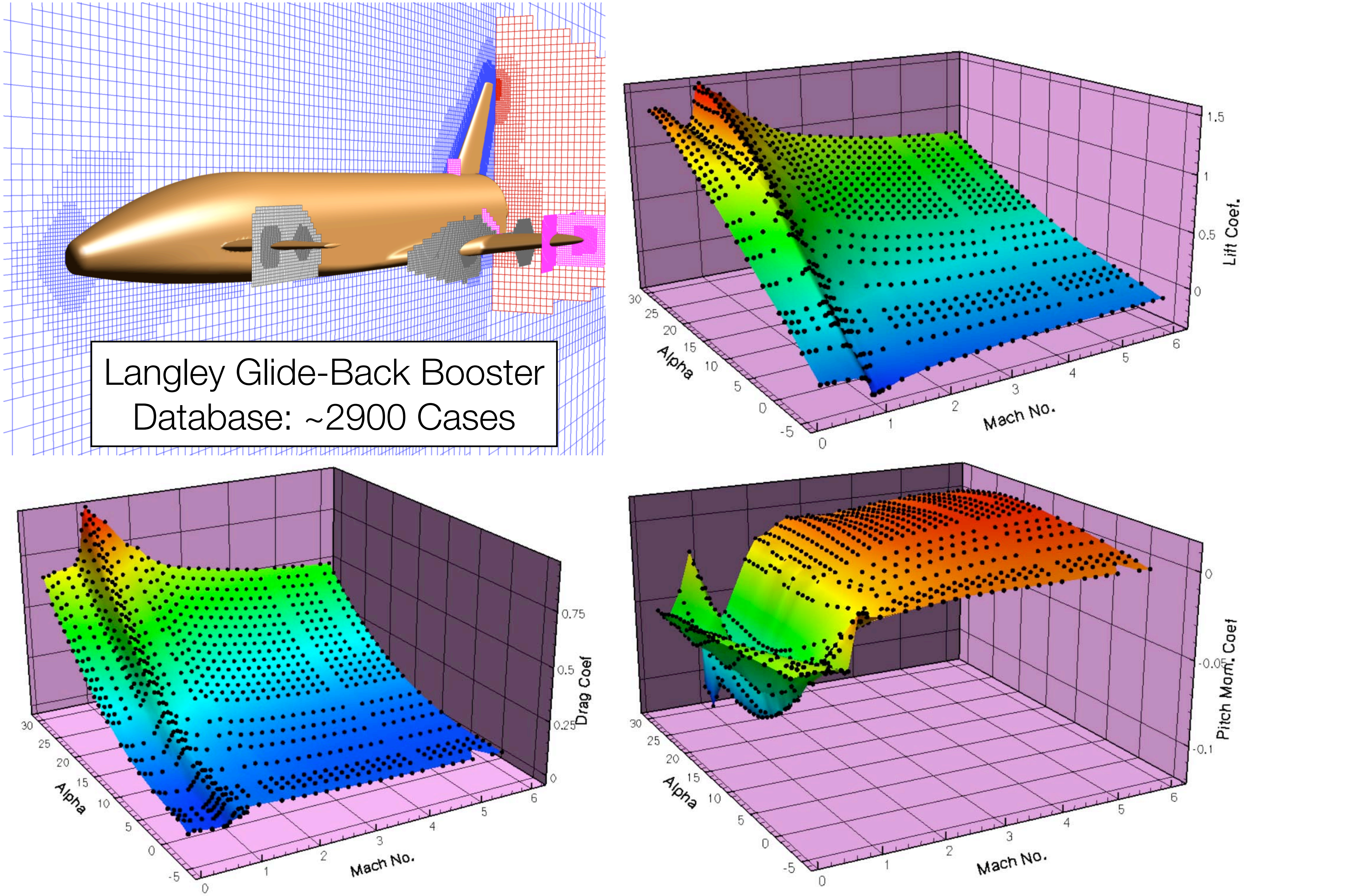
ELORET Corp. NASA Ames

Advanced Supercomputing Division
NASA Ames Research Center

47th AIAA Aerospace Sciences Meeting, Orlando, FL
January 11, 2009

Oral Presentation Only

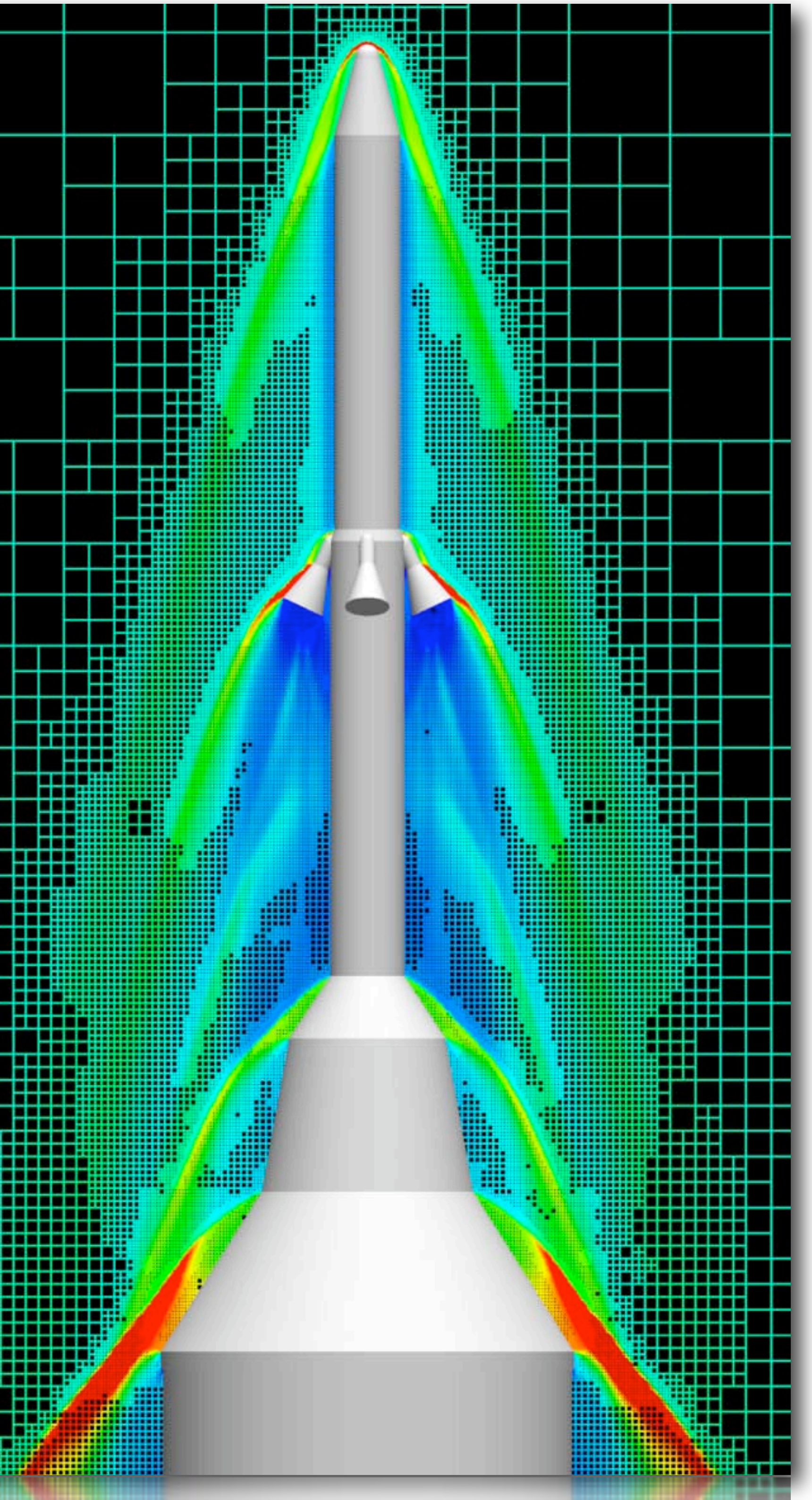
Motivation



- How well is the vehicle's aerodynamic performance estimated?
- Is the mesh appropriate for every flow condition and vehicle configuration?

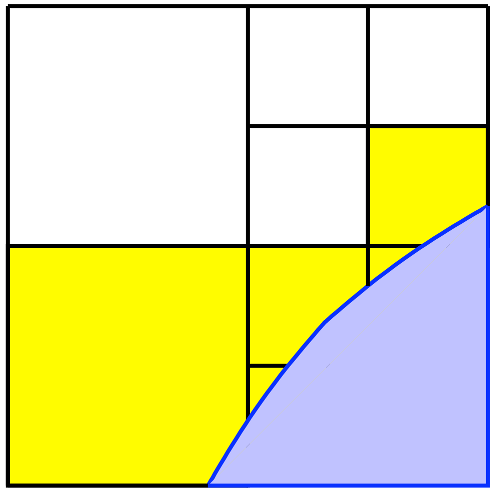
Objectives

Toward automation of CFD analysis

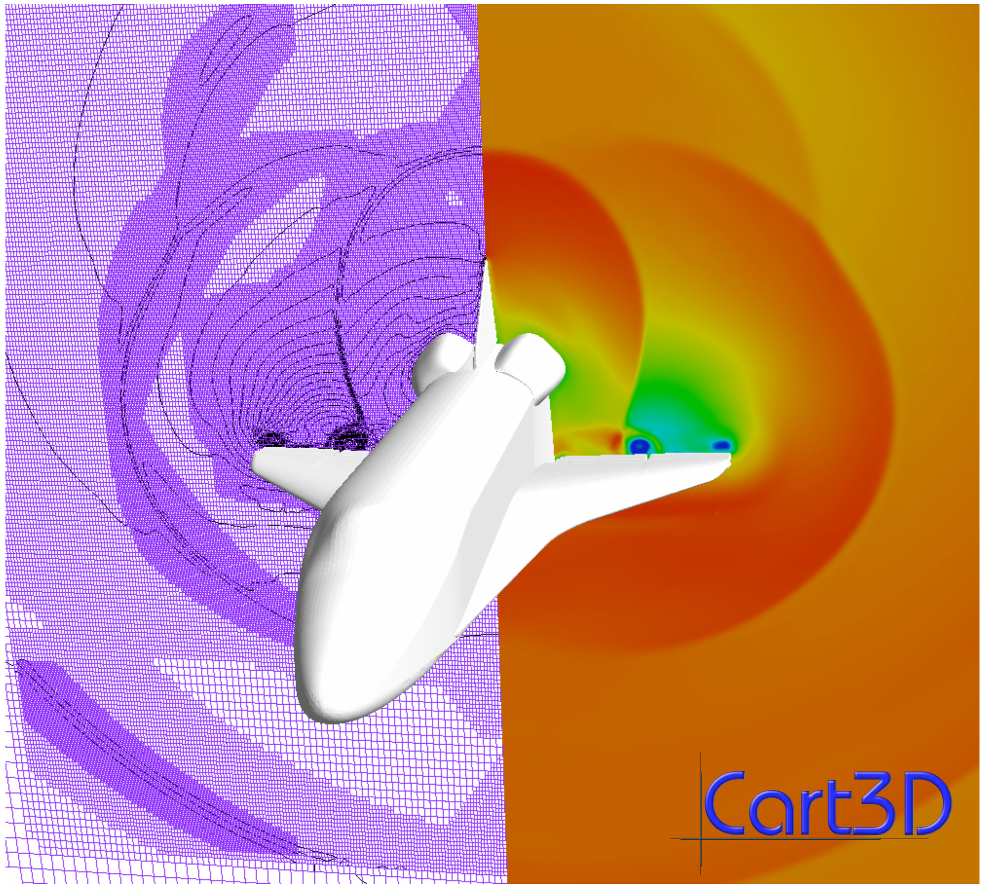


- Handle complex geometry problems
- Control discretization errors via solution-adaptive mesh refinement
- Focus on aerodynamic databases of parametric and optimization studies
  1. **Accuracy**: satisfy prescribed error bounds
  2. **Robustness** and **speed**: may require over 10^5 mesh generations
  3. **Automation**: avoid user supervision
- Obtain “expert meshes” independent of user skill
- Run every case adaptively in production settings

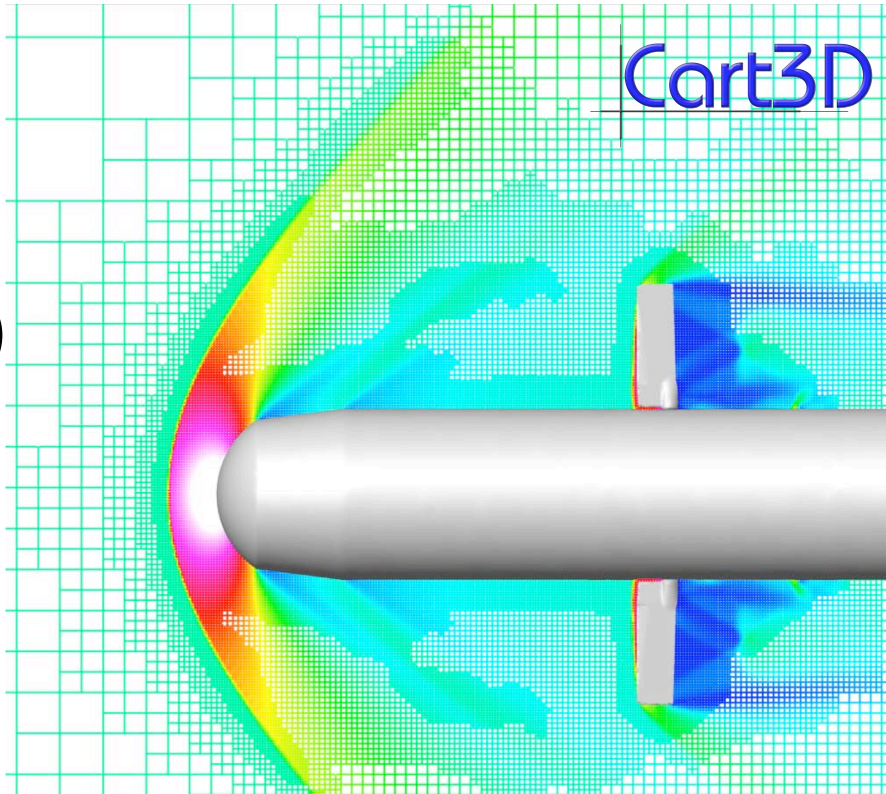
Approach



1. Embedded-boundary Cartesian mesh method (1990's)
   - Arbitrarily complex domains, efficient and accurate
   - Irregularity confined to body intersecting cells

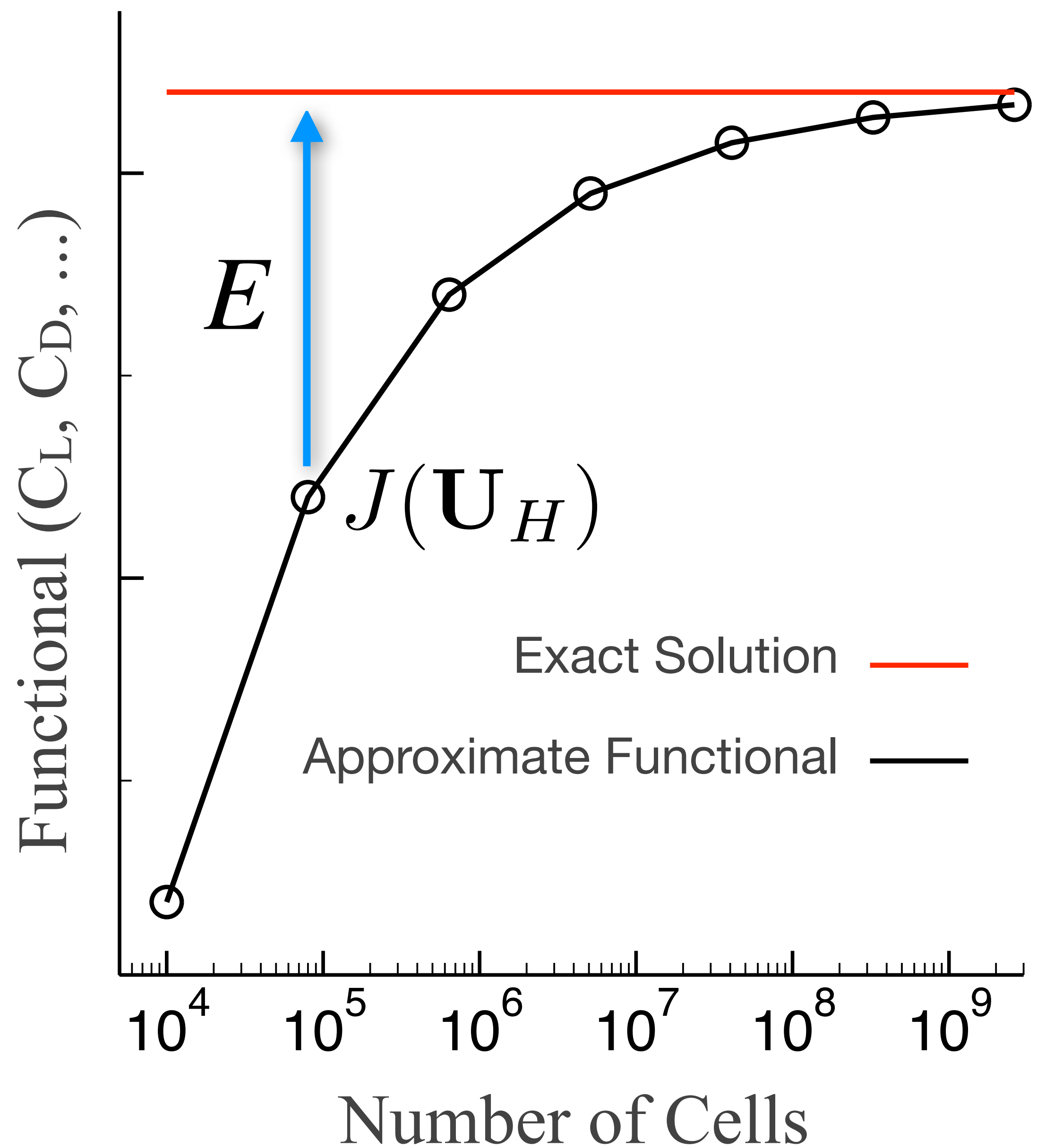


2. Incremental strategy for h-refinement of nested Cartesian meshes (2002)
   - Fast local re-meshing of flagged cells
   - Guaranteed reliability
   - Early work used feature detection and τ-extrapolation



3. Adjoint-weighted residual error estimates (2007)
   - Mesh enrichment targets output functionals
   - Functional error-bound estimates
   - Implementation exploits nesting of Cartesian meshes for fast interpolation

Numerical Error
Uniform Mesh Refinement



Exact Functional: $\mathcal{J}$

- Numerical solution on a mesh with cell-size *H* gives approximate functional:

$$J(\mathbf{U}_H)$$

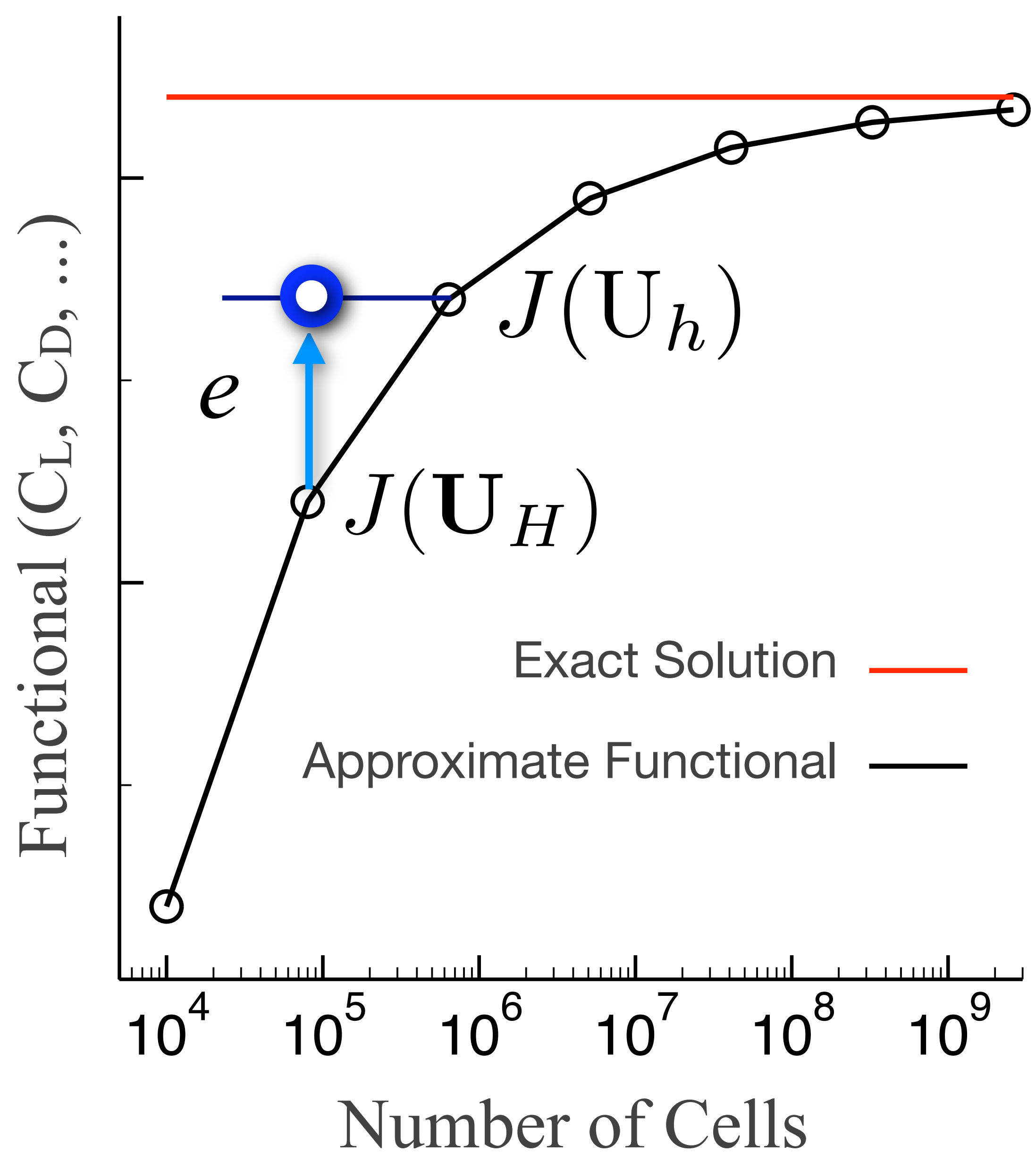
- Goal is to estimate functional error:

$$\mathcal{J}(\mathbf{U}) = J(\mathbf{U}_H) + E$$

- Express the error as a function of the flow solution

$$E = f(\mathbf{U}_H)$$

Discrete Estimate of Numerical Error



- Consider a simpler problem of computing relative error:

$$J(\mathbf{U}_h) = J(\mathbf{U}_H) + e$$

- For second-order accurate spatial discretization and cell-size in the asymptotic range, the functional error is:

$$E = e + \frac{1}{4}e + \frac{1}{4^2}e + \cdots$$
$$= \frac{4}{3}e$$

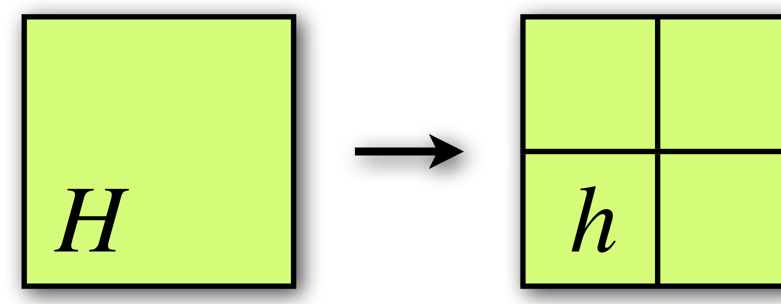
- We will use an adjoint solution on mesh *H* to estimate

$$e = f(\mathbf{U}_H, \psi_H)$$

Adjoint Error Estimates

- Consider a functional $J(\mathbf{U}_H)$ computed from the solution of Euler equations discretized on an affordable mesh with cell-size H:

$$R(\mathbf{U}_H) = 0$$



- In addition, consider an embedded mesh with cell-size h obtained via uniform refinement of the baseline mesh

- We seek to compute the error relative to the embedded mesh without solving the problem on the fine mesh

$$e = |J(\mathbf{U}_h) - J(\mathbf{U}_h^H)|$$

Venditti & Darmofal, 2002

- Estimate of functional on embedded mesh is obtained from Taylor series expansions about the coarse mesh solution

$$J(\mathbf{U}_h) \approx J(\mathbf{U}_h^H) + \frac{\partial J(\mathbf{U}_h^H)}{\partial \mathbf{U}_h}(\mathbf{U}_h - \mathbf{U}_h^H)$$

$$\mathbf{R}(\mathbf{U}_h) = 0 \approx \mathbf{R}(\mathbf{U}_h^H) + \frac{\partial \mathbf{R}(\mathbf{U}_h^H)}{\partial \mathbf{U}_h}(\mathbf{U}_h - \mathbf{U}_h^H)$$

- These equations are combined to give

$$J(\mathbf{U}_h) \approx J(\mathbf{U}_h^H) - \psi_h^{\mathrm{T}}\,\mathbf{R}(\mathbf{U}_h^H)$$

where ψ satisfies the adjoint equation

$$\left[\frac{\partial \mathbf{R}(\mathbf{U}_h^H)}{\partial \mathbf{U}_h}\right]^{\mathrm{T}} \psi_h = \frac{\partial J(\mathbf{U}_h^H)}{\partial \mathbf{U}_h}^{\mathrm{T}}$$

- Estimate of functional on embedded mesh is obtained from Taylor series expansions about the coarse mesh solution

$$J(\mathbf{U}_h) \approx J(\mathbf{U}_h^H) + \frac{\partial J(\mathbf{U}_h^H)}{\partial \mathbf{U}_h}(\mathbf{U}_h - \mathbf{U}_h^H)$$

$$\mathbf{R}(\mathbf{U}_h) = 0 \approx \mathbf{R}(\mathbf{U}_h^H) + \frac{\partial \mathbf{R}(\mathbf{U}_h^H)}{\partial \mathbf{U}_h}(\mathbf{U}_h - \mathbf{U}_h^H)$$

- These equations are combined to give

$$J(\mathbf{U}_h) \approx J(\mathbf{U}_h^H) - \boxed{\psi_h^{\mathrm{T}}\, \mathbf{R}(\mathbf{U}_h^H)} \longrightarrow$$

Adjoints provide a weighting on residual errors

where ψ satisfies the adjoint equation

$$\left[\frac{\partial \mathbf{R}(\mathbf{U}_h^H)}{\partial \mathbf{U}_h}\right]^{\mathrm{T}} \psi_h = \frac{\partial J(\mathbf{U}_h^H)}{\partial \mathbf{U}_h}^{\mathrm{T}}$$

Adjoint Correction and Error Bound

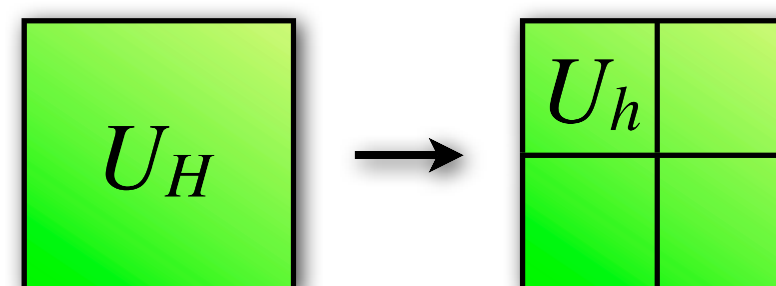
- Since the adjoint solution is not known on the embedded mesh, we use an approximate solution from the coarse mesh to obtain

$$J(\mathbf{U}_h) \approx J(\mathbf{U}_h^H) - (\psi_h^H)^{\mathrm{T}}\mathbf{R}(\mathbf{U}_h^H) - (\psi_h - \psi_h^H)^{\mathrm{T}}\mathbf{R}(\mathbf{U}_h^H)$$

Adjoint Correction　　Remaining Error

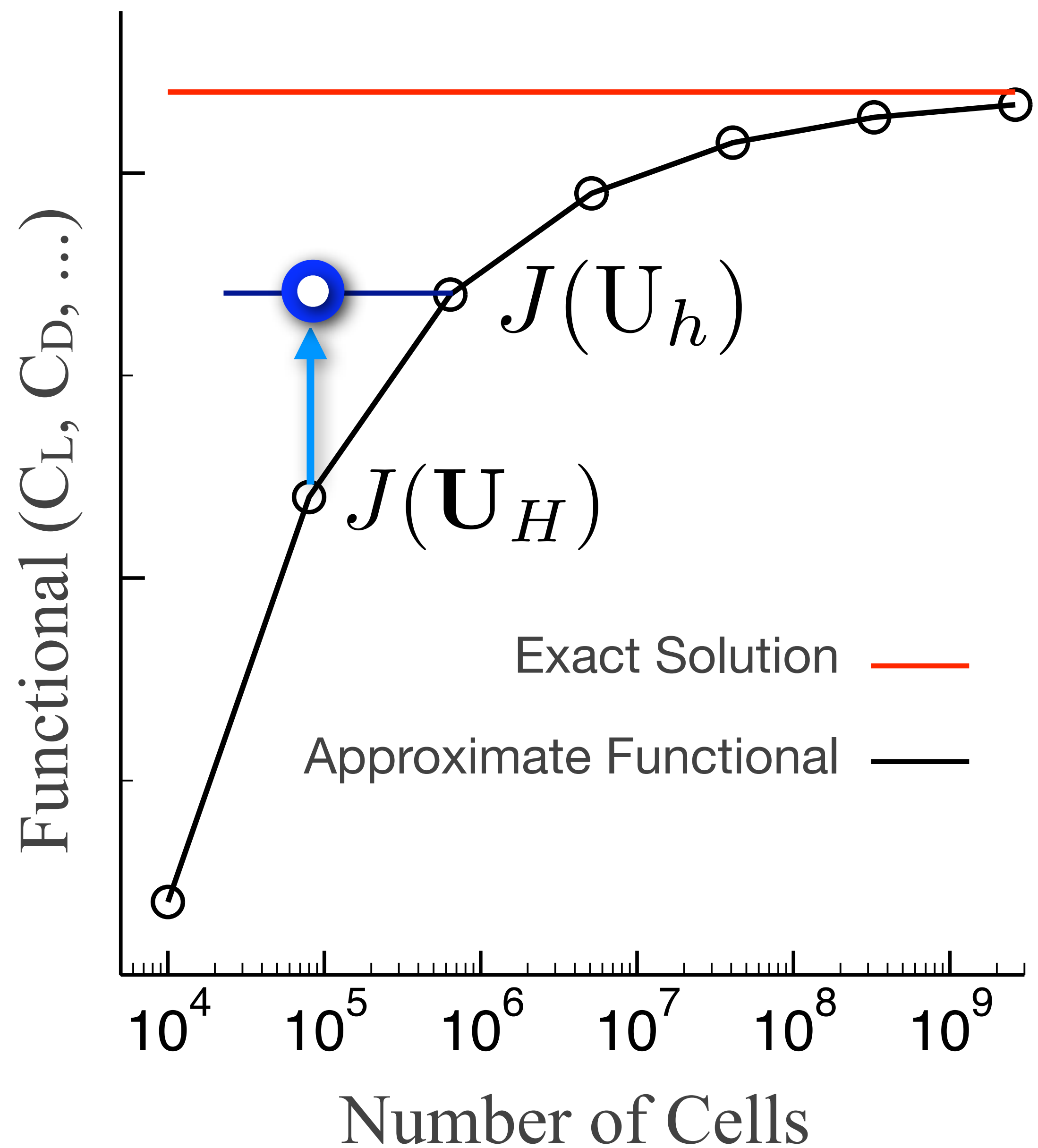
- $\mathbf{U}_h^H, \psi_h^H$ denote reconstructed solutions lifted from coarse mesh to embedded mesh. We use linear interpolation

- ψ_h is unknown. We approximate it with a quadratic interpolant

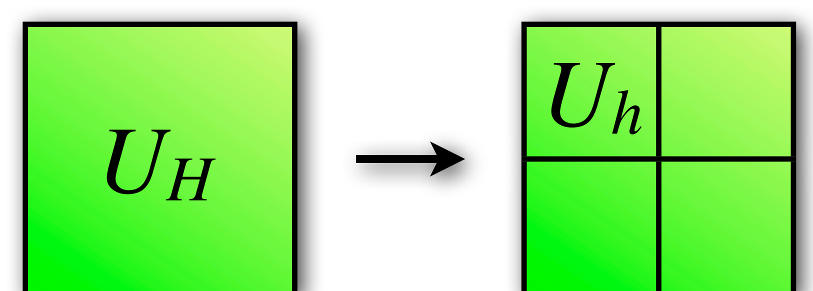


Adjoint Correction

$$\boxed{J(\mathbf{U}_h) \approx J(\mathbf{U}_h^H) - (\psi_h^H)^{\mathrm{T}}\mathbf{R}(\mathbf{U}_h^H)} - (\psi_h - \psi_h^H)^{\mathrm{T}}\mathbf{R}(\mathbf{U}_h^H)$$

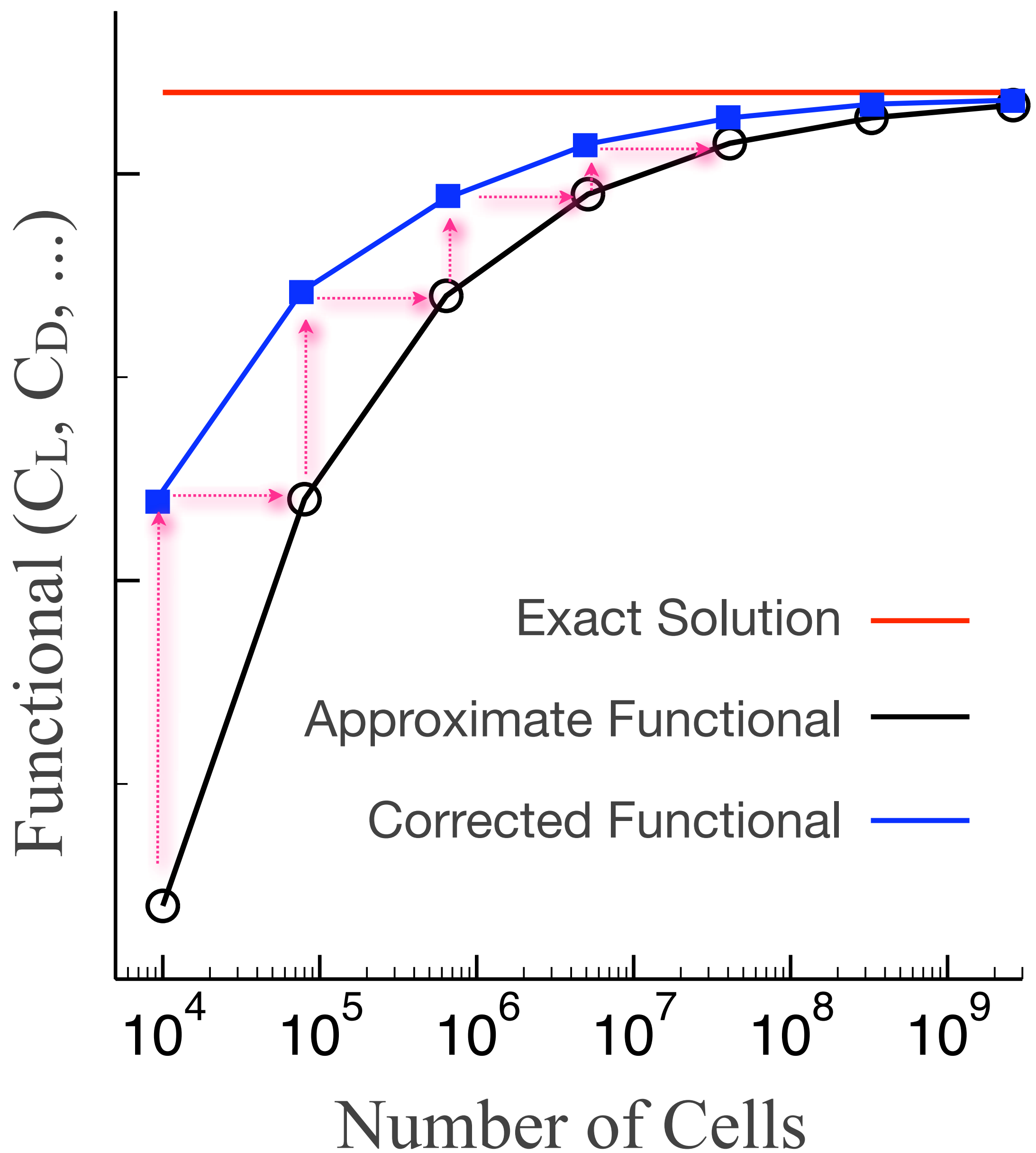


- Predict functional on a fine mesh with cell-size *h* from a coarse mesh solution with cell size *H*

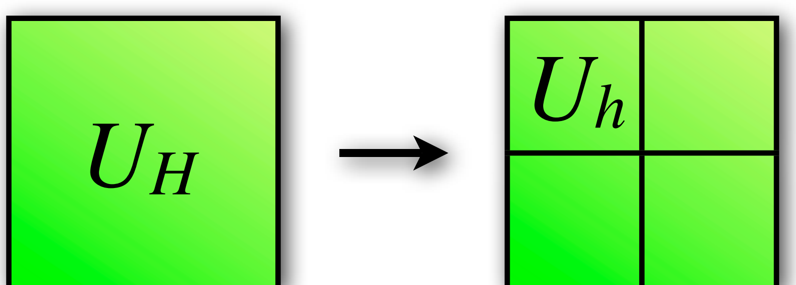


Adjoint Correction

$$\boxed{J(\mathbf{U}_h) \approx J(\mathbf{U}_h^H) - (\psi_h^H)^{\mathrm{T}}\mathbf{R}(\mathbf{U}_h^H)} - (\psi_h - \psi_h^H)^{\mathrm{T}}\mathbf{R}(\mathbf{U}_h^H)$$



- Predict functional on a fine mesh with cell-size *h* from a coarse mesh solution with cell size *H*

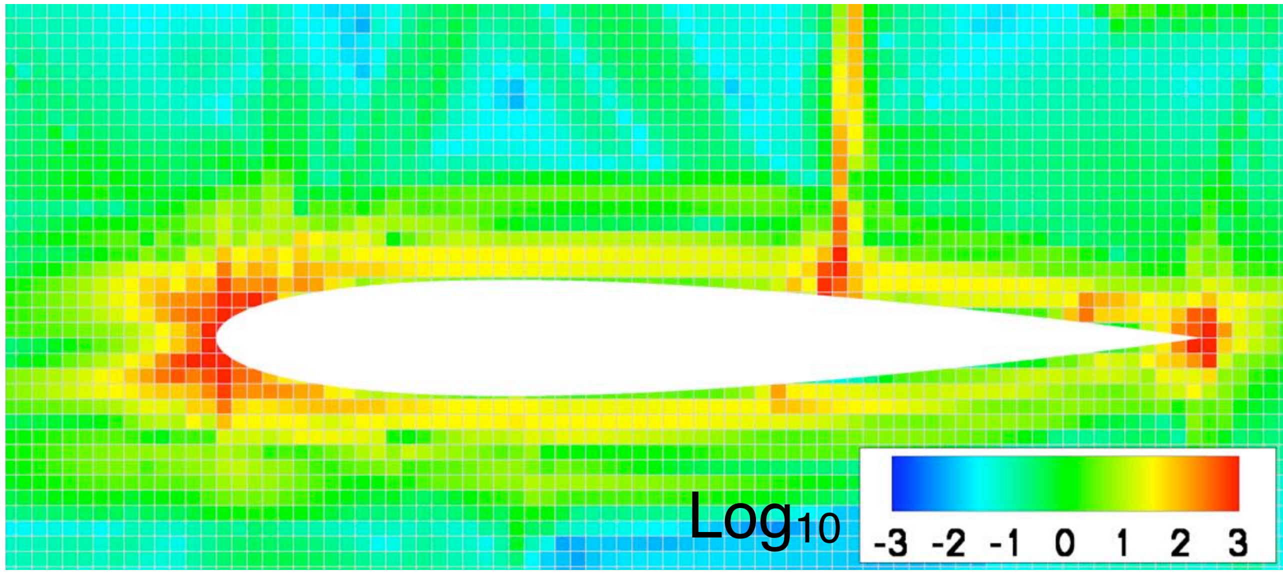


Error Bound Estimate

$$J(\mathbf{U}_h) \approx J(\mathbf{U}_h^H) - (\psi_h^H)^{\mathrm{T}}\mathbf{R}(\mathbf{U}_h^H) - \boxed{(\psi_h - \psi_h^H)^{\mathrm{T}}\mathbf{R}(\mathbf{U}_h^H)}$$

- Bound on remaining error in each coarse cell *k*

$$e_k = \sum \left|(\psi_{\mathrm{Q}} - \psi_{\mathrm{L}})^{\mathrm{T}} R(\mathbf{U}_{\mathrm{L}})\right|_k$$



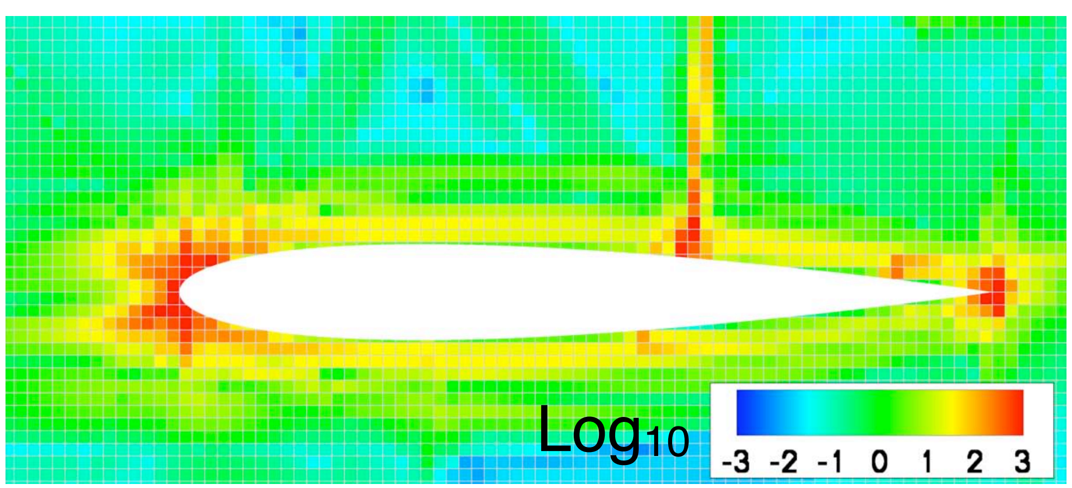
- Net functional error $E = \sum_{k=0}^{N} e_k$

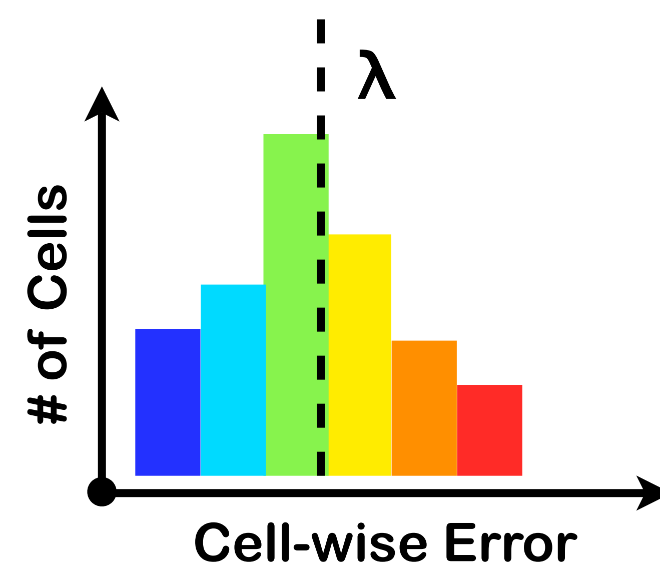
- Given a user specified tolerance TOL, termination criterion is satisfied when E < TOL

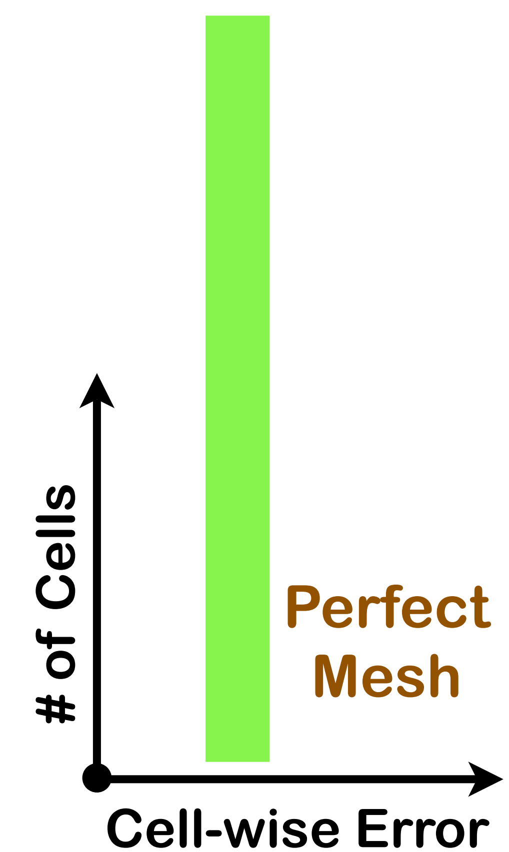
Refinement Parameter

- Define maximum allowable error level in each coarse cell via equidistribution: t = TOL / N
- Refinement parameter in each cell is given by $r_k = \dfrac{e_k}{t}$
- Refine cells for which $r_k > \lambda$
  where $\lambda \geq 1$ is a global threshold factor

Error Histograms







Results
Focus on Applications

Part A. Accuracy

- Launch Abort Vehicle with jets - uniform mesh refinement study

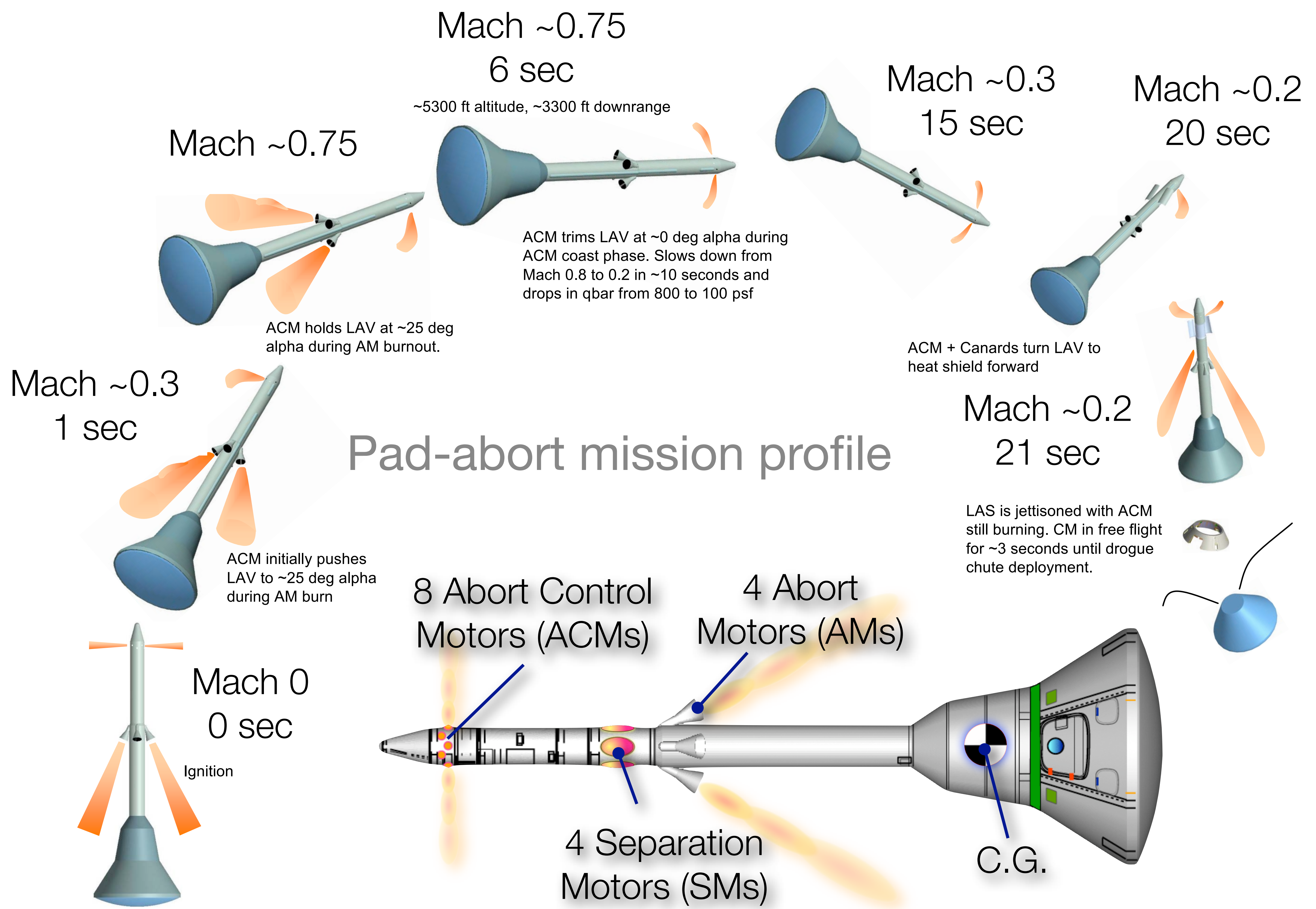
Part B. Efficiency

- Sonic-boom signature test case - computational cost summary

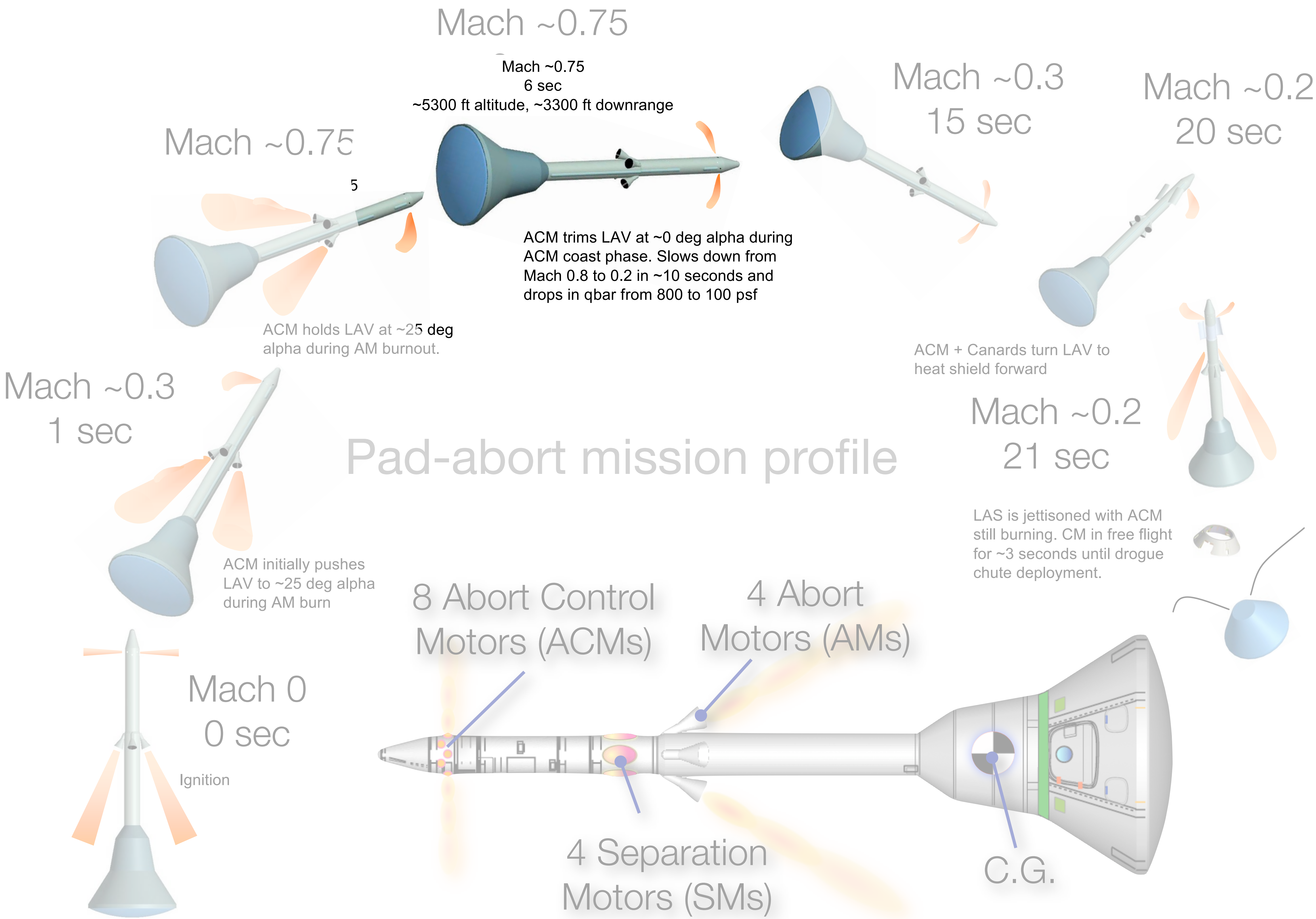
Part C. Databases

- Nozzle-Guide-Vane Missile
- Launch Abort Vehicle with Jettison Motor plumes

Launch Abort Vehicle with ACM Jets



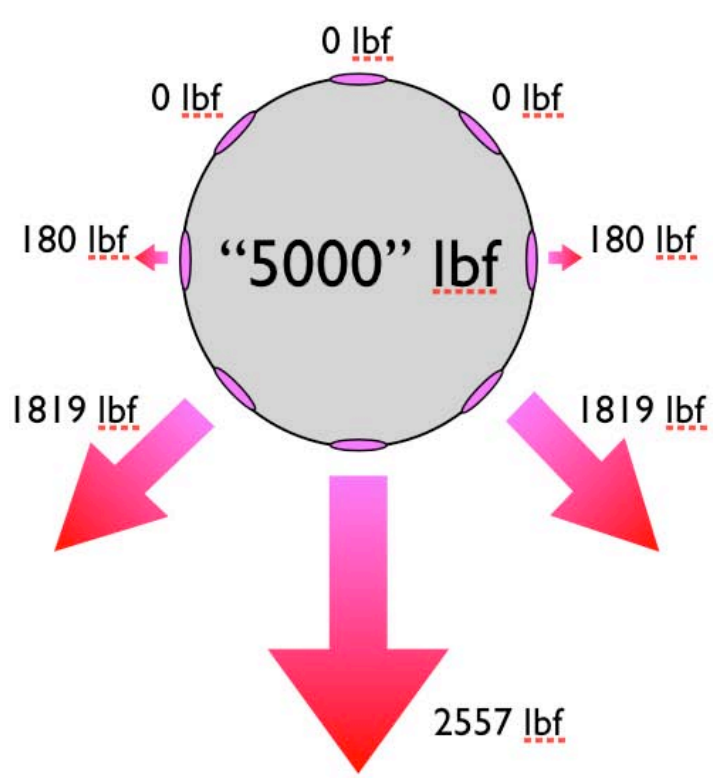
Launch Abort Vehicle with ACM Jets

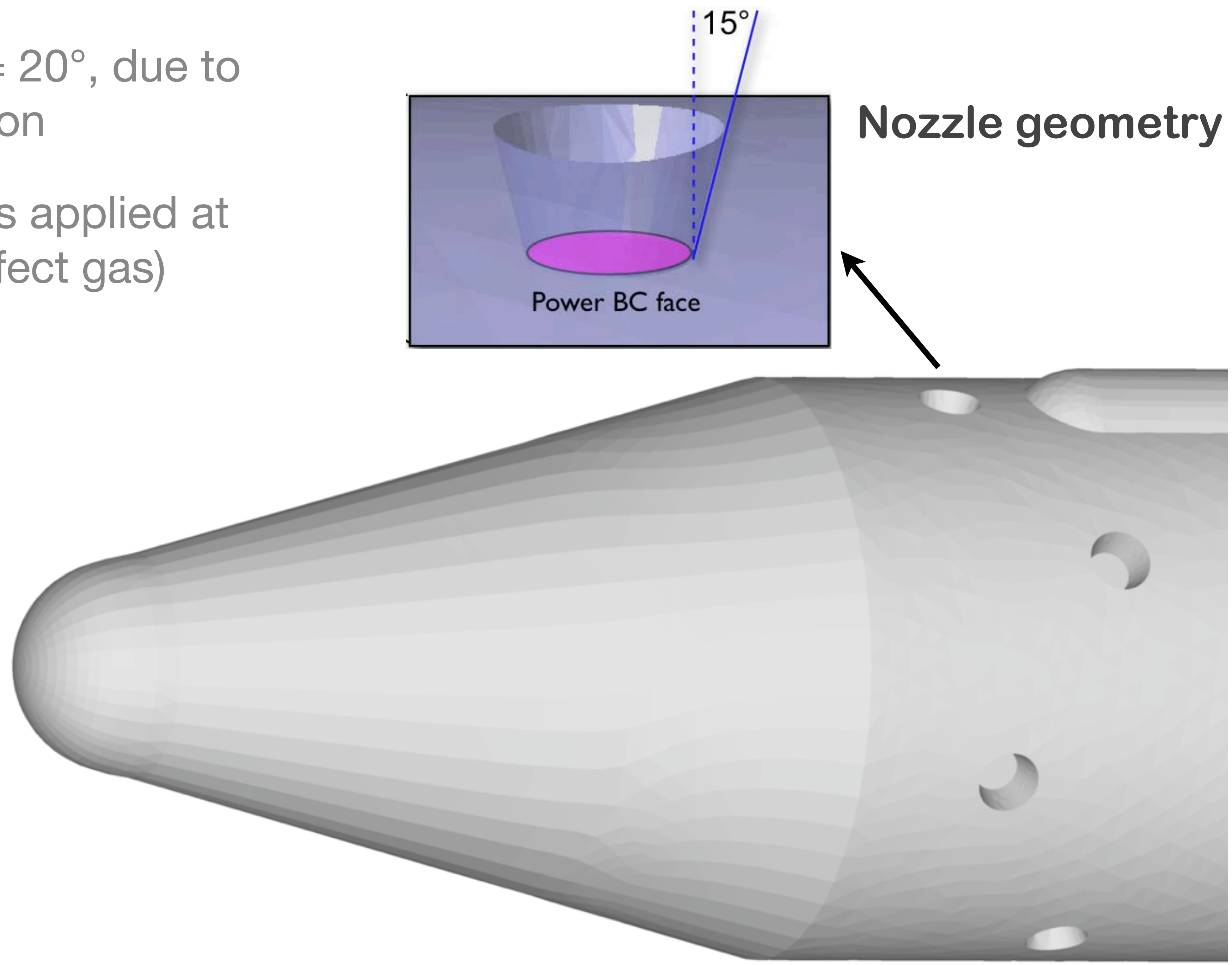


Launch Abort Vehicle with ACM Jets
Problem Setup

- Examine aerodynamic performance with ACM jets (AIAA 2008-1281)
- Selected case: $M_\infty = 4$, $\alpha = 20°$, due to significant plume penetration
- Power boundary conditions applied at plenum face (assumes perfect gas)

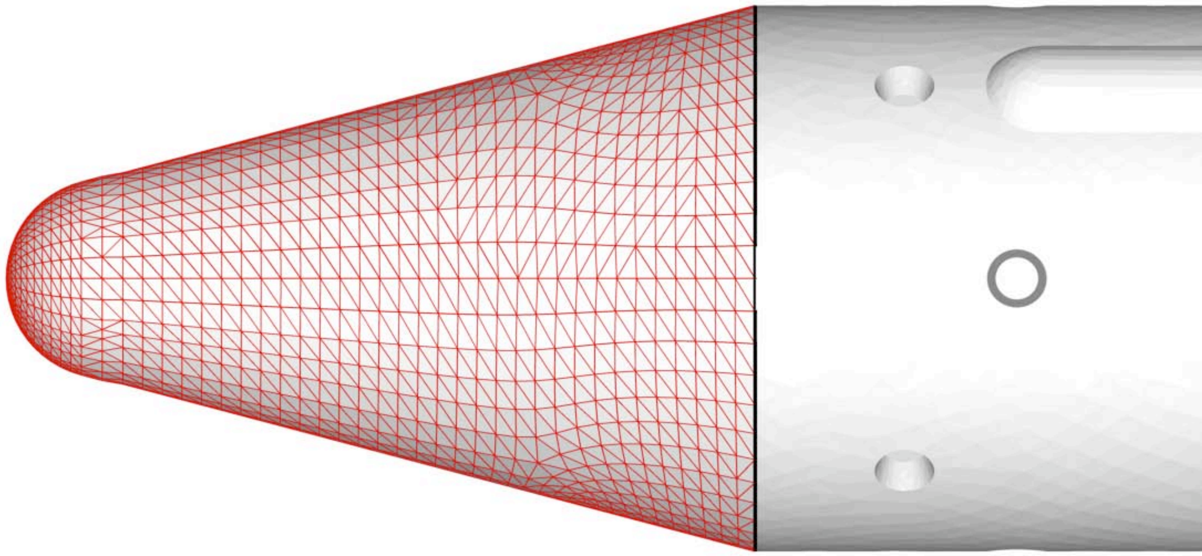
Thrust setting



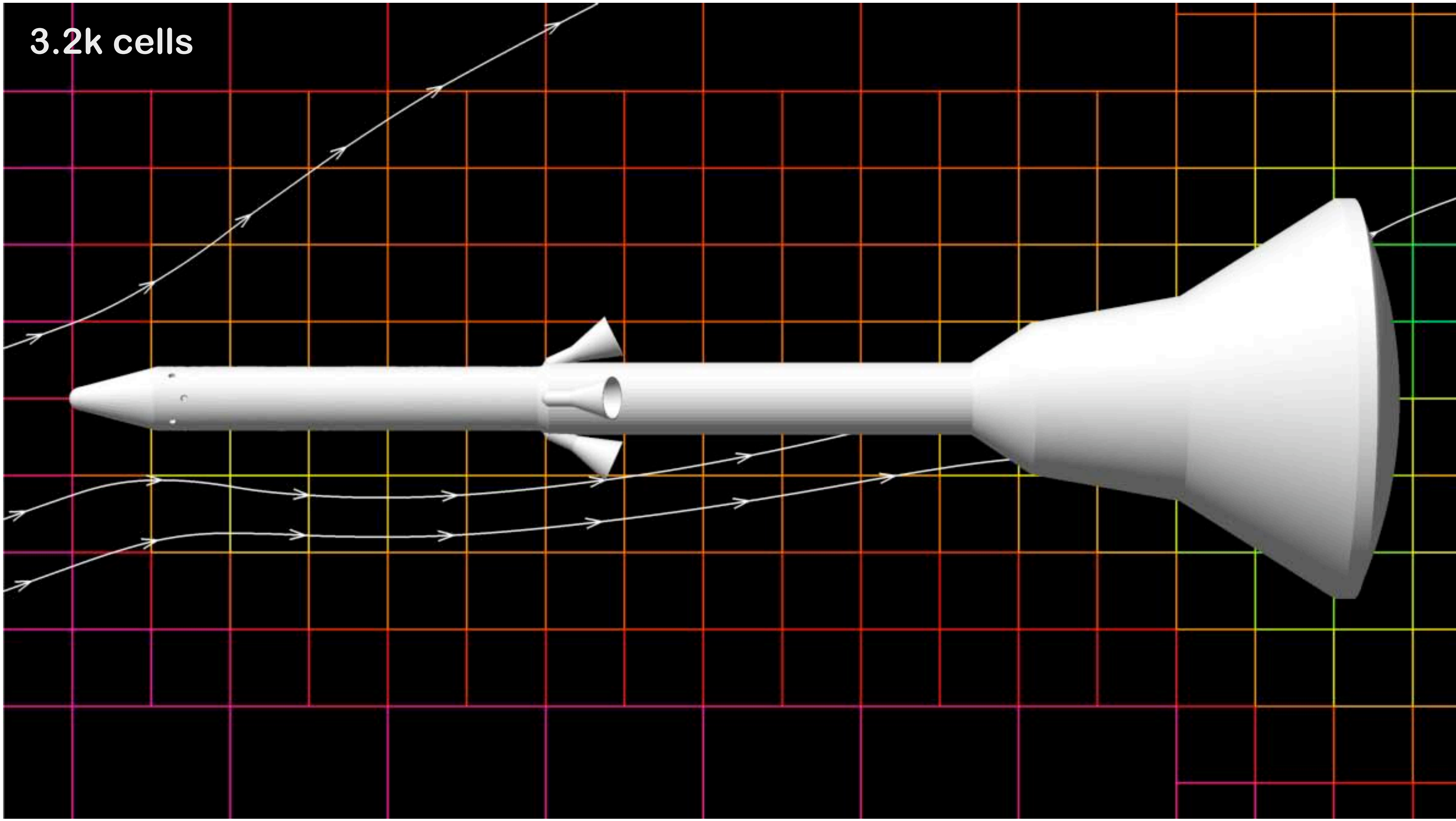


Launch Abort Vehicle with ACM Jets Functional

- Functional: $C_N+0.4C_A$
- Consider two cases:
  - *Case A*: Functional defined over nose-cone surface only, TOL=0.0005
    - Accuracy verification: Uniform mesh refinement study
    - Take advantage of supersonic freestream conditions to limit refinement to nose-cone region
  - *Case B*: Functional defined over entire vehicle, TOL=0.006
    - Typical engineering database case

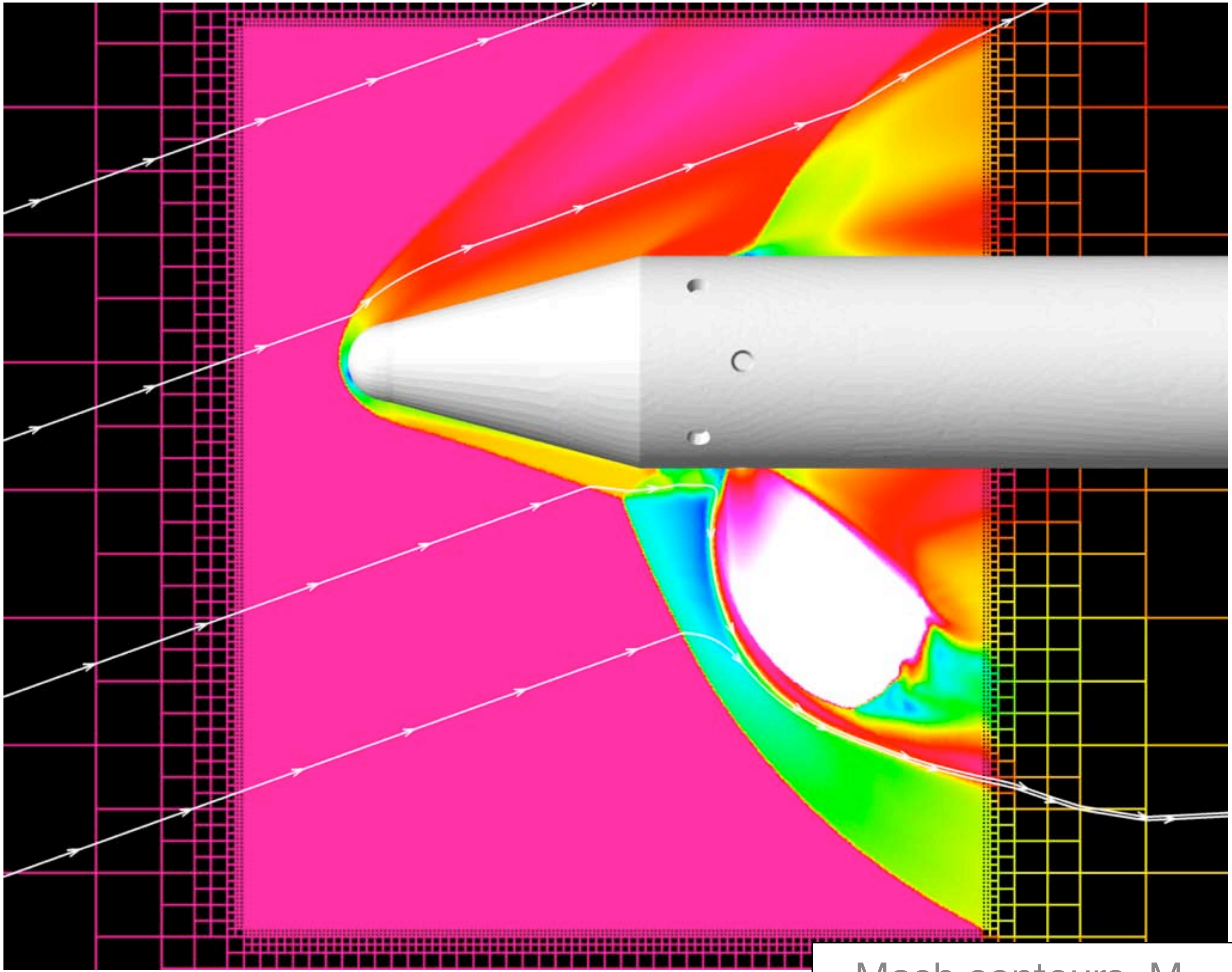


Launch Abort Vehicle
Initial mesh and solution on symmetry plane



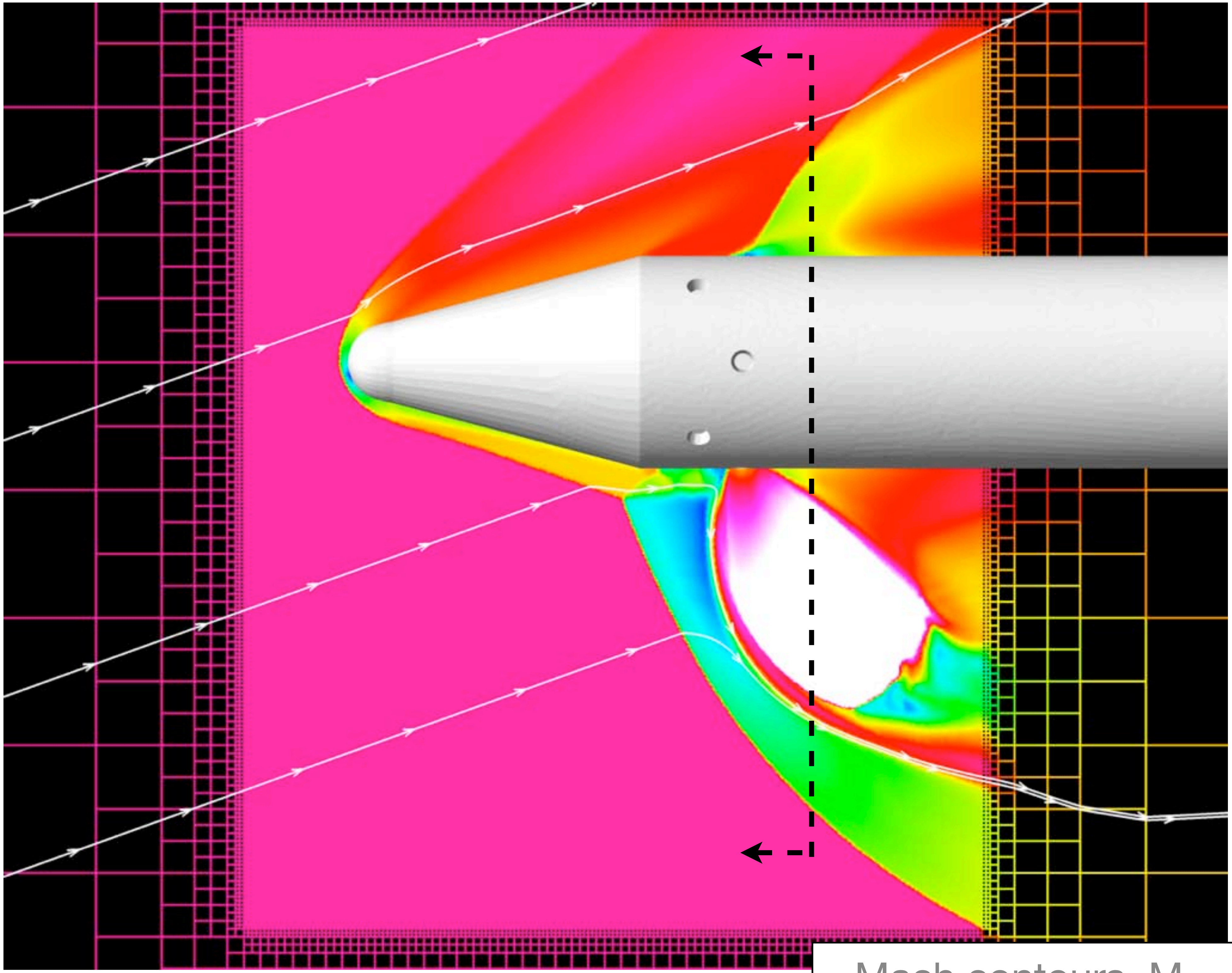
Mach contours, $M_\infty = 4$, $\alpha = 20°$

Case A: Finest Mesh of Uniform Refinement Study (Side-view, 75M Cells)



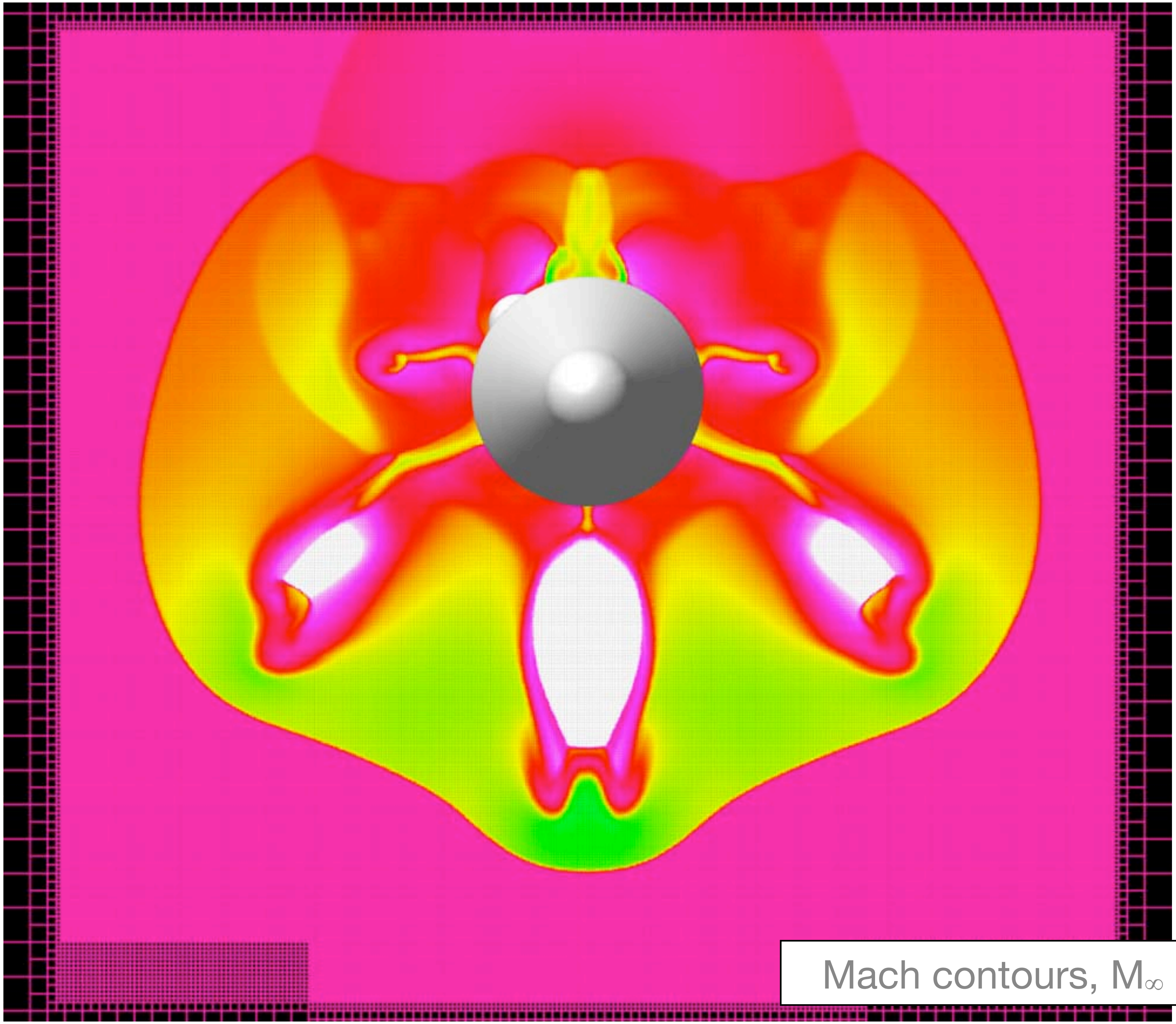
Mach contours, $M_\infty = 4$, $\alpha = 20°$

Case A: Finest Mesh of Uniform Refinement Study (Side-view, 75M Cells)



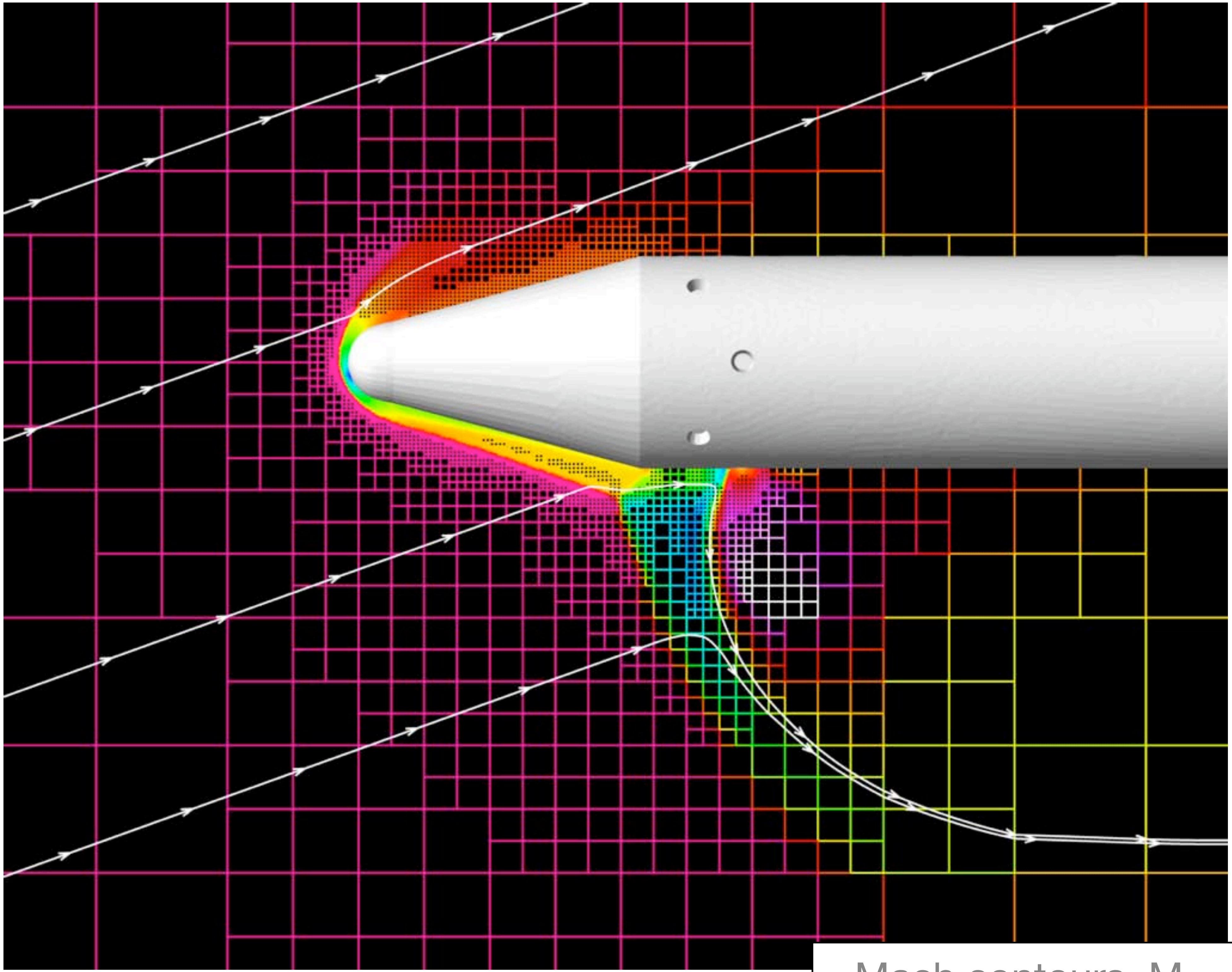
Mach contours, $M_\infty = 4$, $\alpha = 20°$

Case A: Finest Mesh of Uniform Refinement Study (Front-view, 75M Cells)



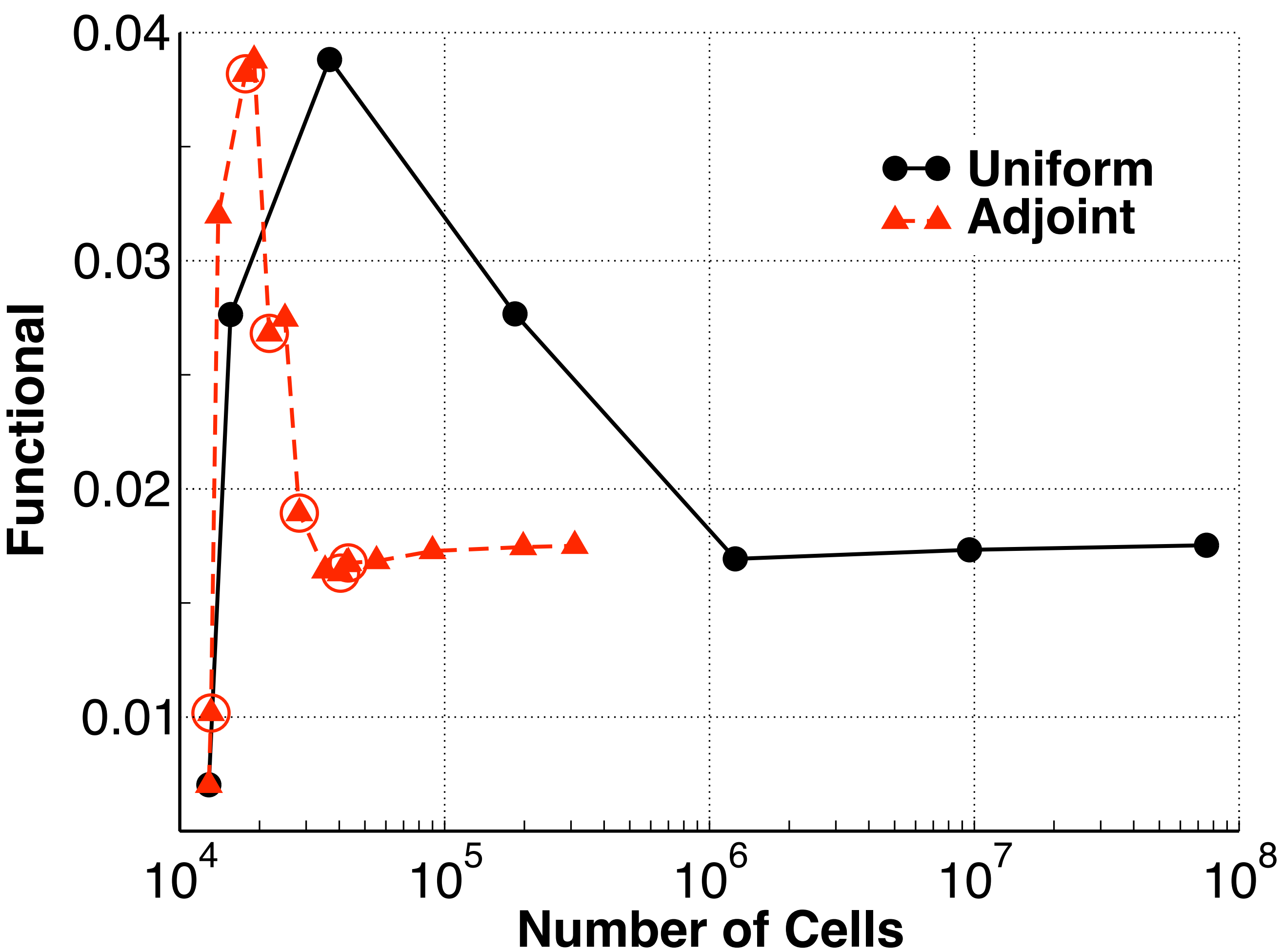
Mach contours, $M_\infty = 4$, $\alpha = 20°$

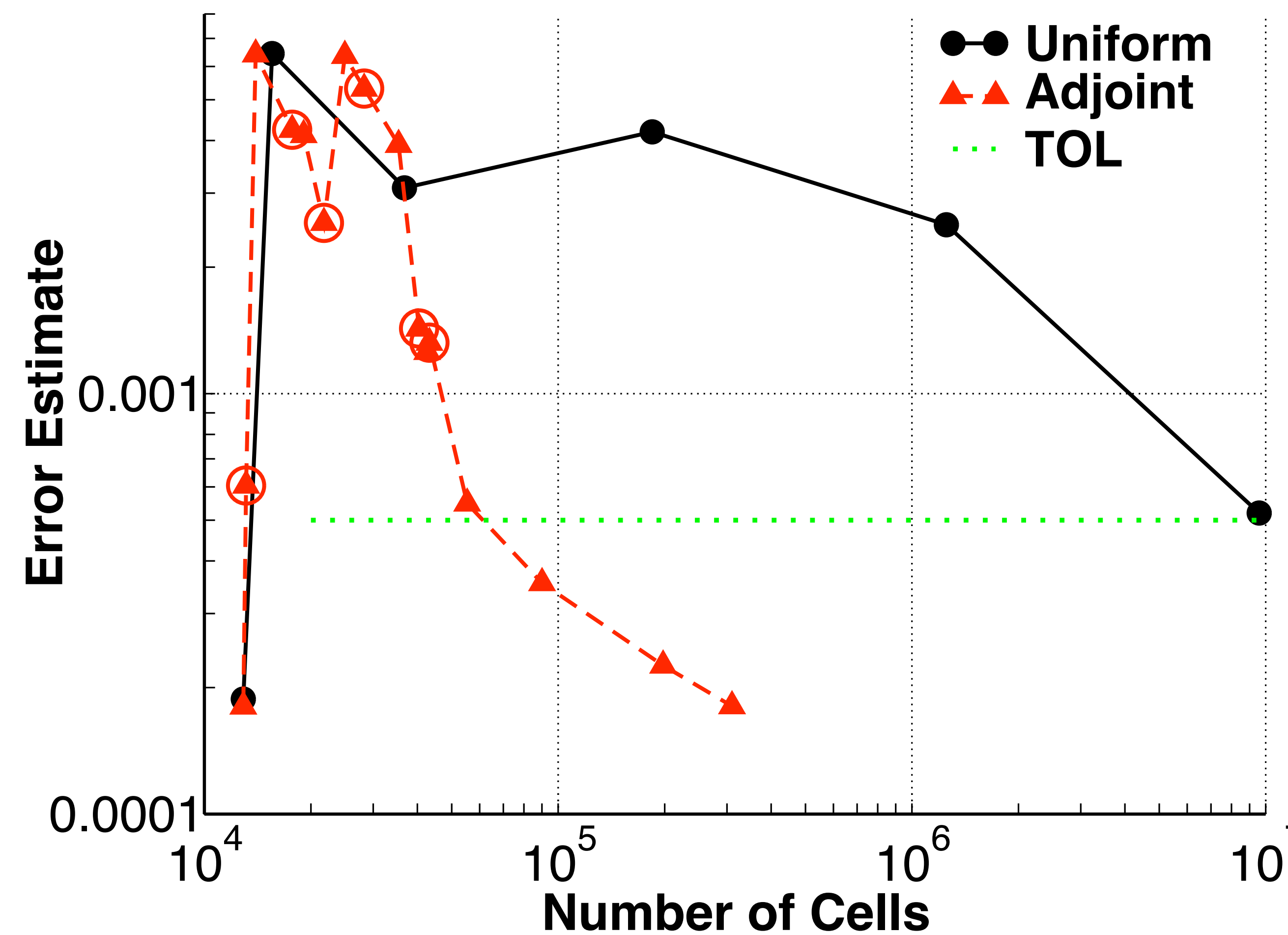
Case A: Adapted Mesh (Side-view)
14 Cycles; 310k Cells



Mach contours, $M_\infty = 4$, $\alpha = 20°$

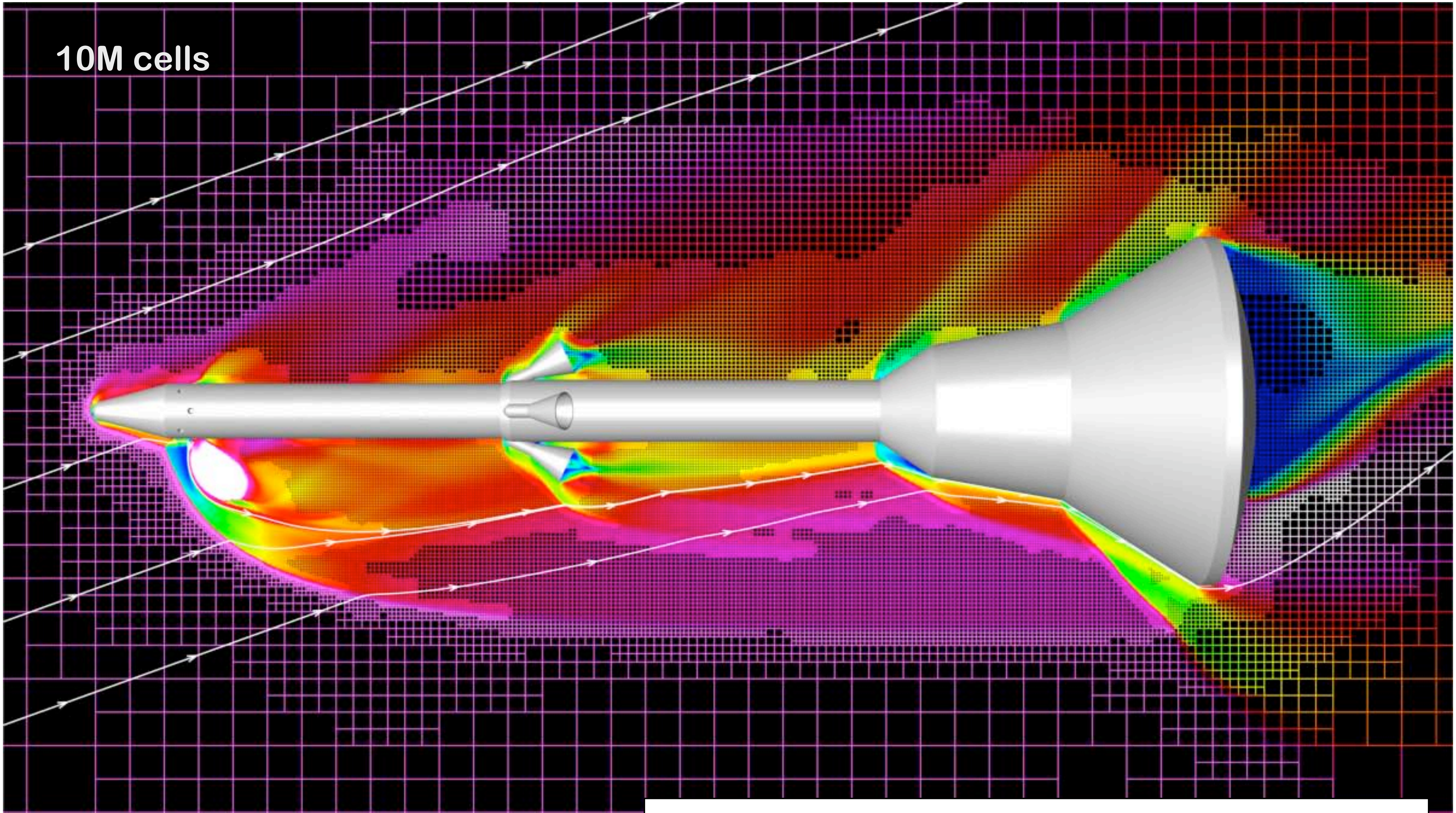
Case A: Functional and Error Convergence





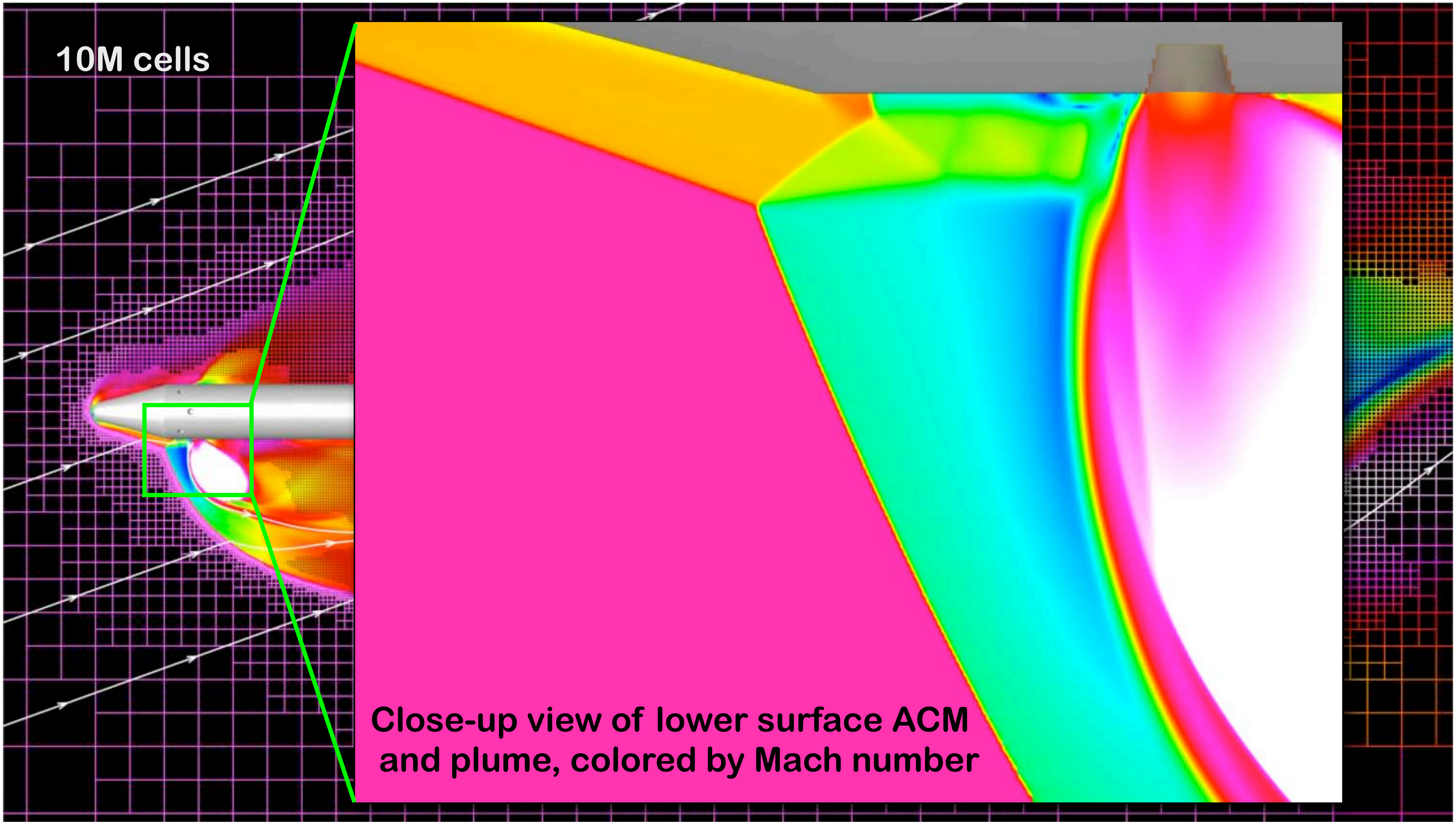
- Difference in functional values is below 0.05% on finest mesh
- Two orders-of magnitude savings in total number of cells
- Adaptive computation required just 9 minutes of wall-clock time on an 8-core Intel Xeon desktop

Case B
Final mesh and solution on symmetry plane

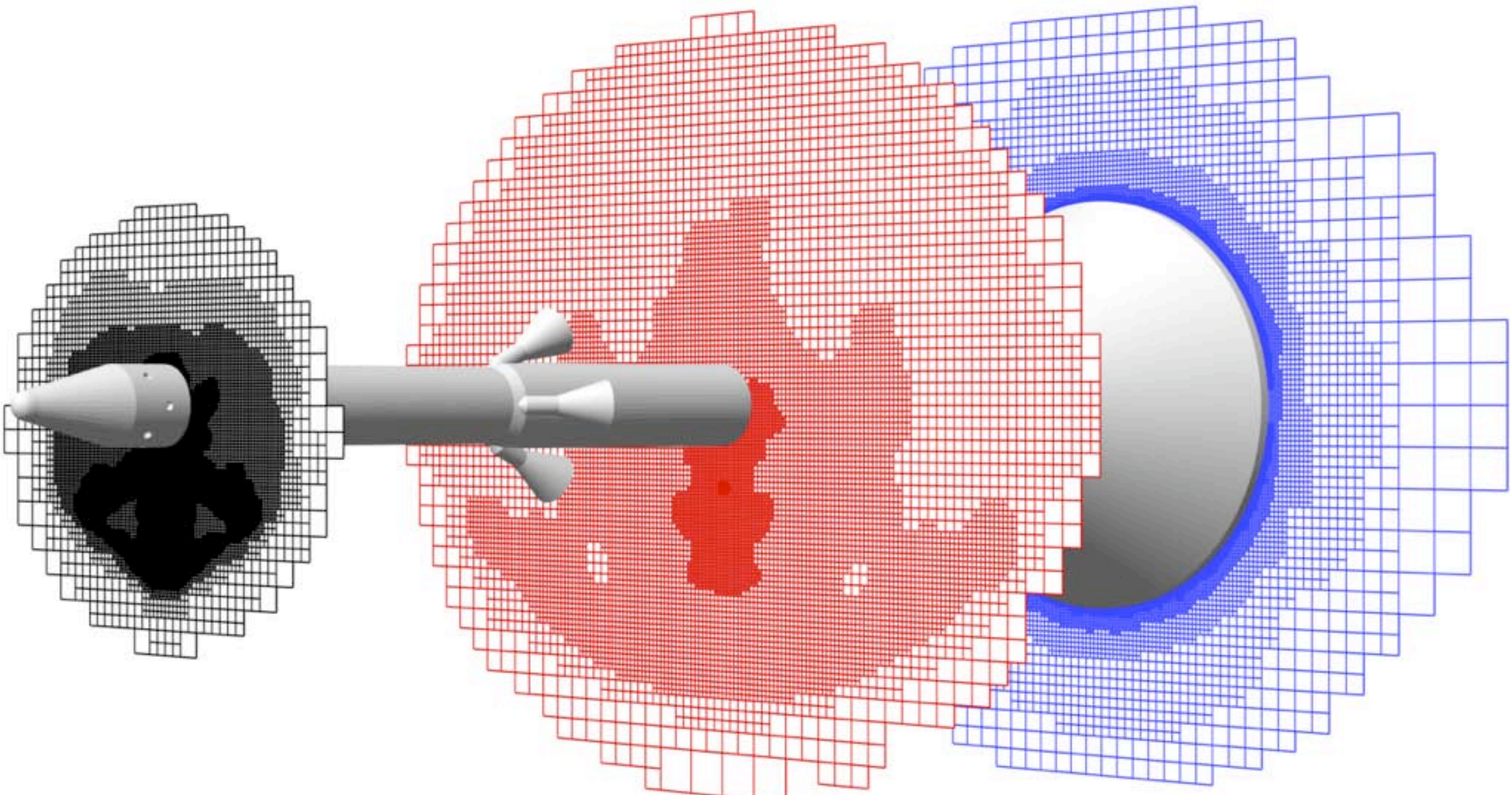


15 adaptations, Mach contours, $M_\infty = 4$, $\alpha = 20°$

Case B
Type IV Shock-Shock Interference

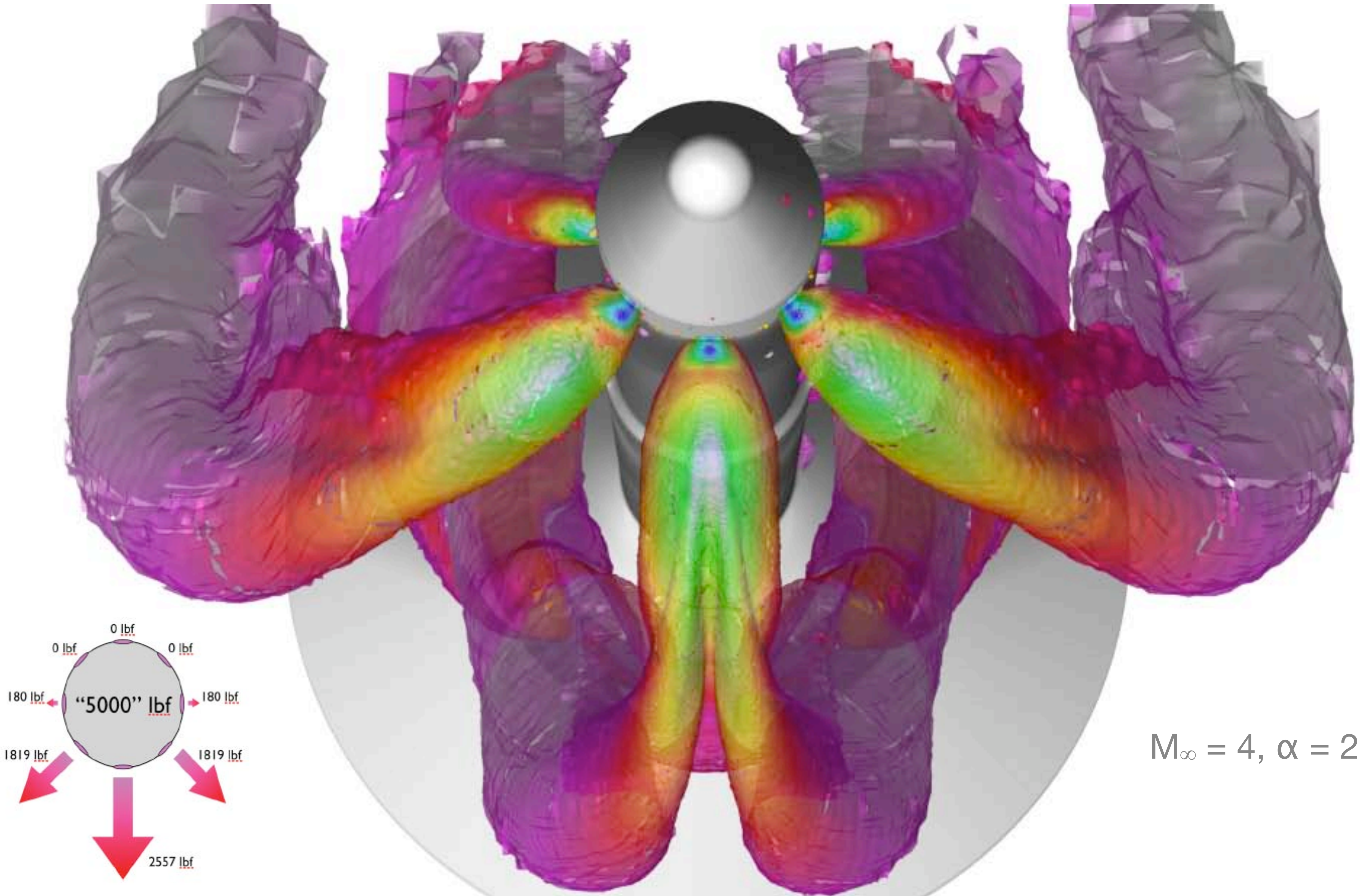


Case B
Final mesh at various x-stations



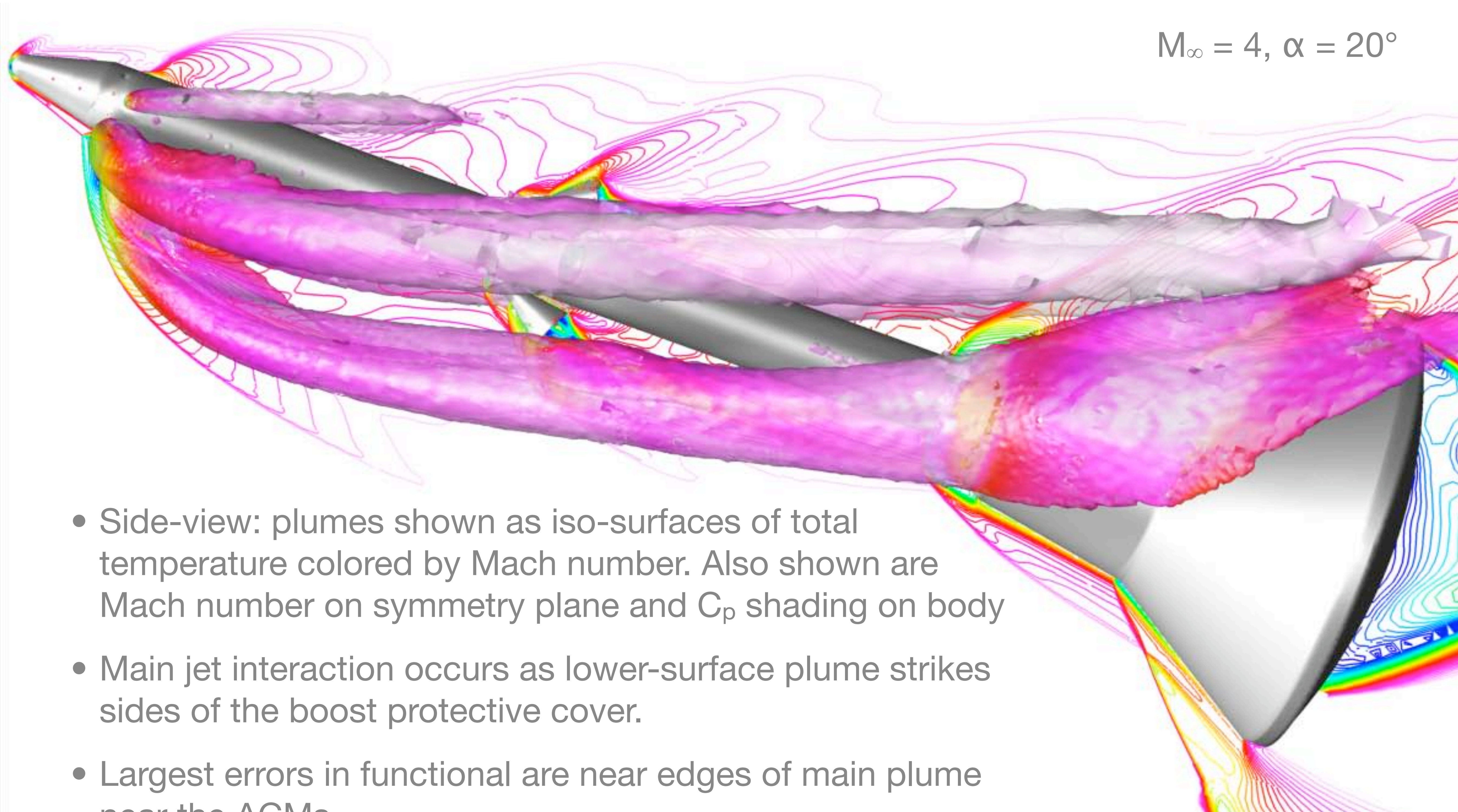
15 adaptations, $M_\infty = 4$, $\alpha = 20°$

Case B
Front view of plumes on final mesh



$M_\infty = 4$, $\alpha = 20°$

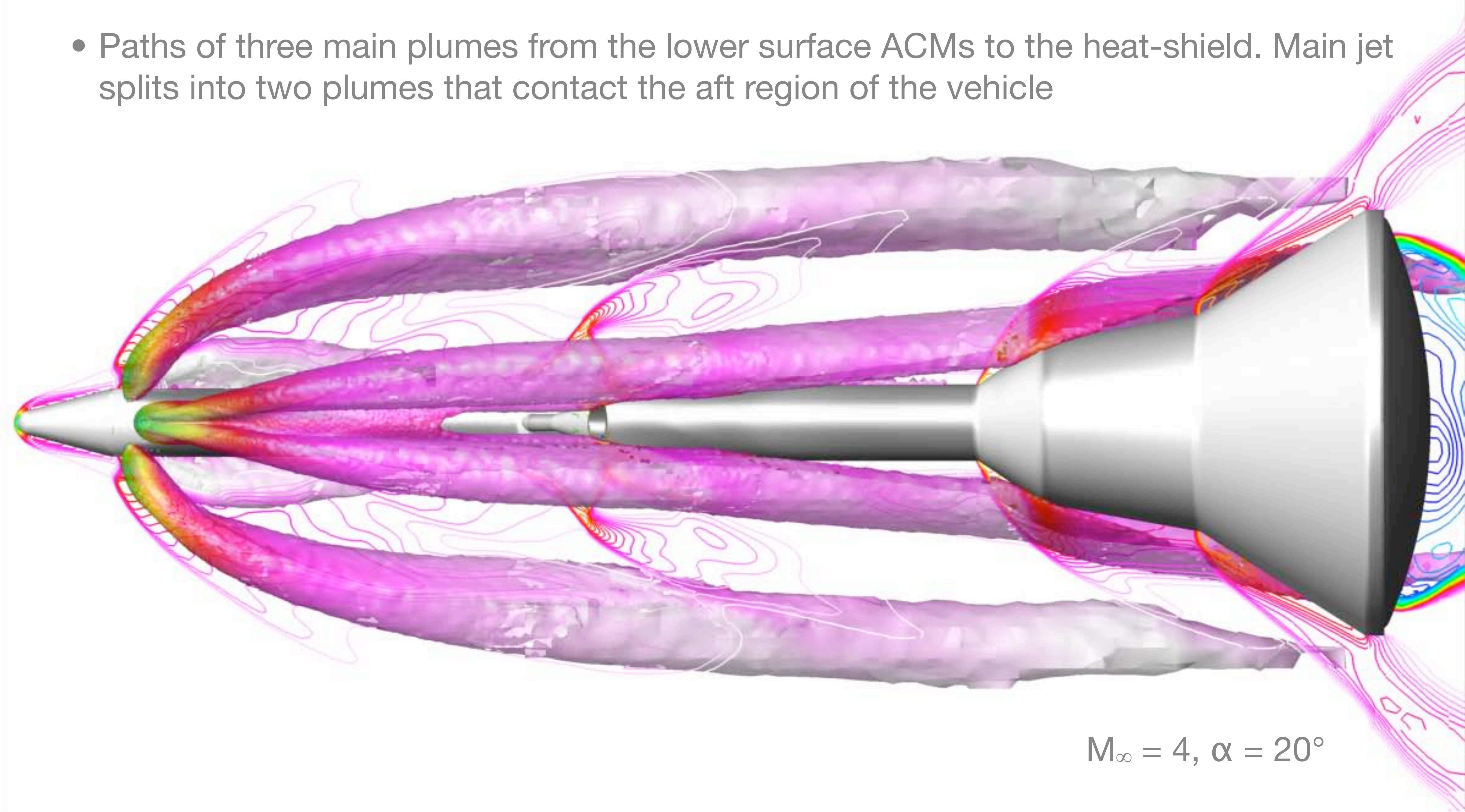
Launch Abort Vehicle
Plume Visualization on Final Mesh (~7.7M cells)



- Side-view: plumes shown as iso-surfaces of total temperature colored by Mach number. Also shown are Mach number on symmetry plane and C_p shading on body
- Main jet interaction occurs as lower-surface plume strikes sides of the boost protective cover.
- Largest errors in functional are near edges of main plume near the ACMs

Launch Abort Vehicle
Bottom view of plumes on final mesh

- Paths of three main plumes from the lower surface ACMs to the heat-shield. Main jet splits into two plumes that contact the aft region of the vehicle



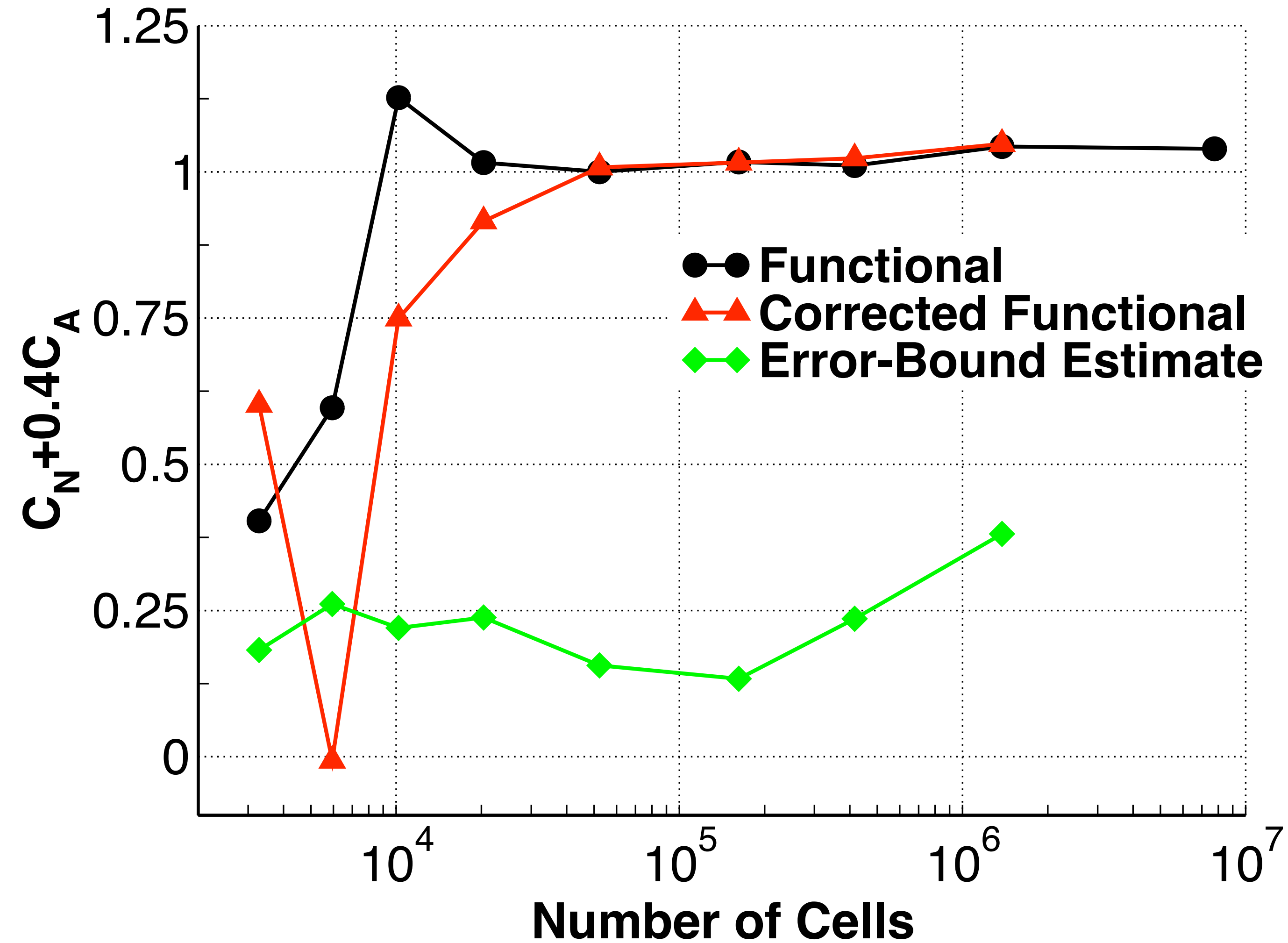
$M_\infty = 4$, $\alpha = 20°$

Launch Abort Vehicle Functional Convergence

- Determination of plume paths and appropriate refinement of plume edges is not possible *a-priori,* yet these features determine the “aerodynamic shape” of the vehicle

- Adjoint error analysis identifies regions where jet interaction effects are important for the computation of aerodynamic coefficients and triggers mesh refinement

- Functional convergence settles down at ~1M cells, however, additional research is required to improve estimates of the error-bound



Results
Focus on Applications

Part A. Accuracy

- Launch Abort Vehicle with jets - uniform mesh refinement study

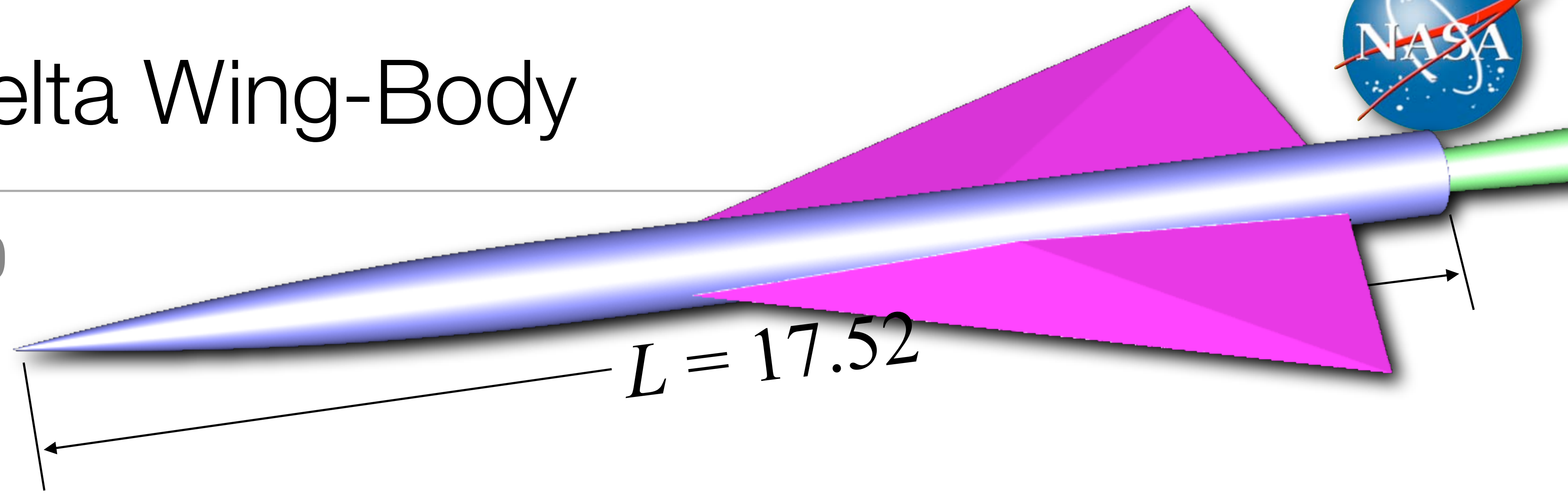
Part B. Efficiency

- Sonic-boom signature test case - computational cost summary

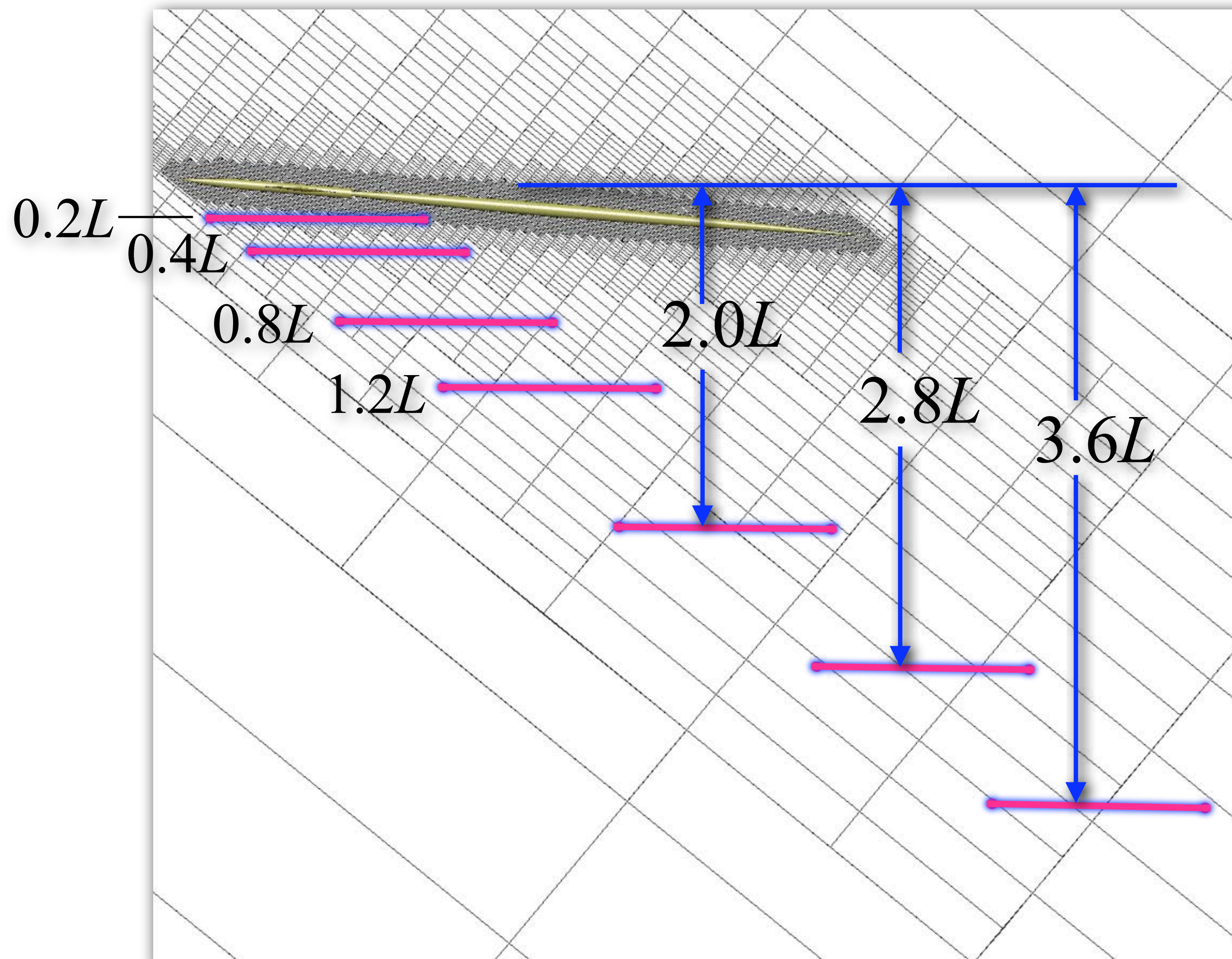
Part C. Databases

- Nozzle-Guide-Vane Missile
- Launch Abort Vehicle with Jettison Motor plumes

69° Swept Delta Wing-Body



- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$
  - Sensor offset, $h/L = 3.6$ & $\{0.2, 0.4, 0.8, 1.2, 2.0, 2.8\}$

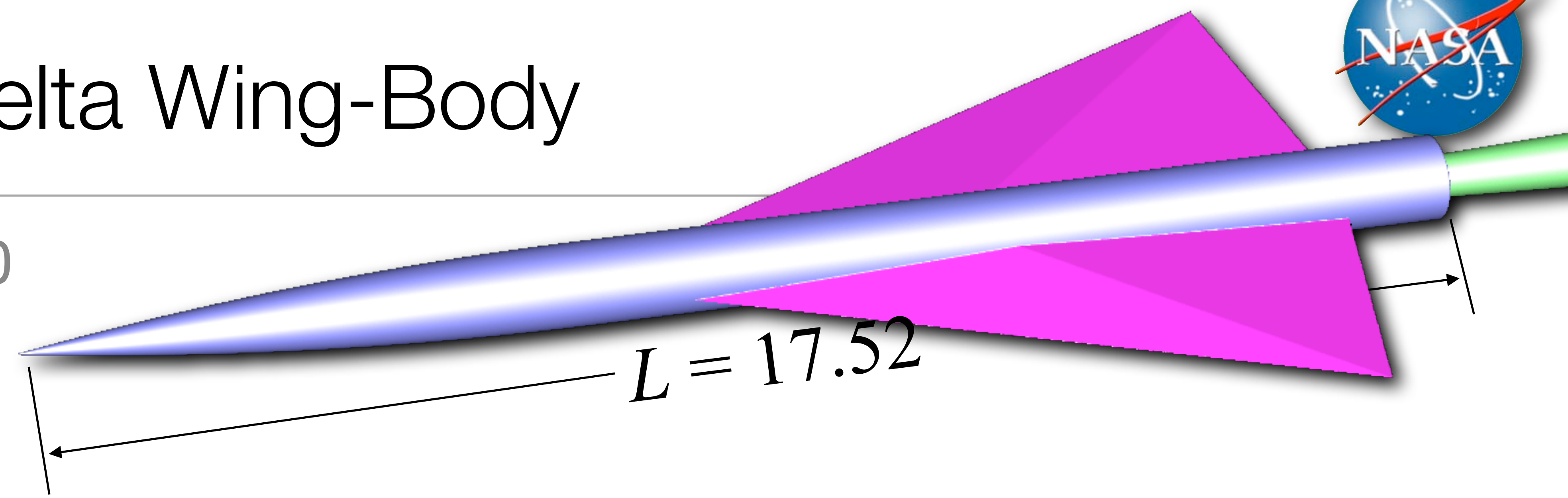


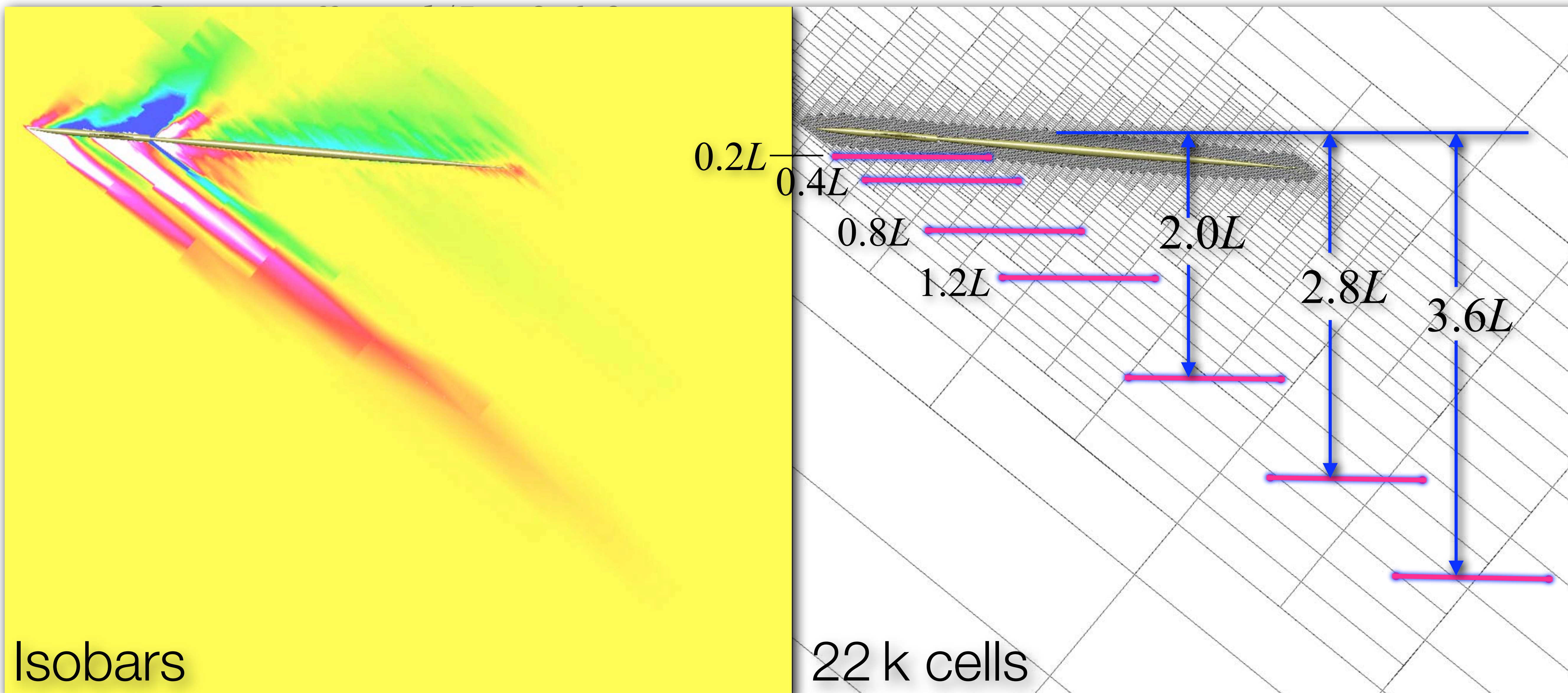
- Initial mesh ~ 22 k cells

$$J_s = \int_0^L \left(\frac{\Delta p}{p_\infty}\right)^2 ds$$

69° Swept Delta Wing-Body

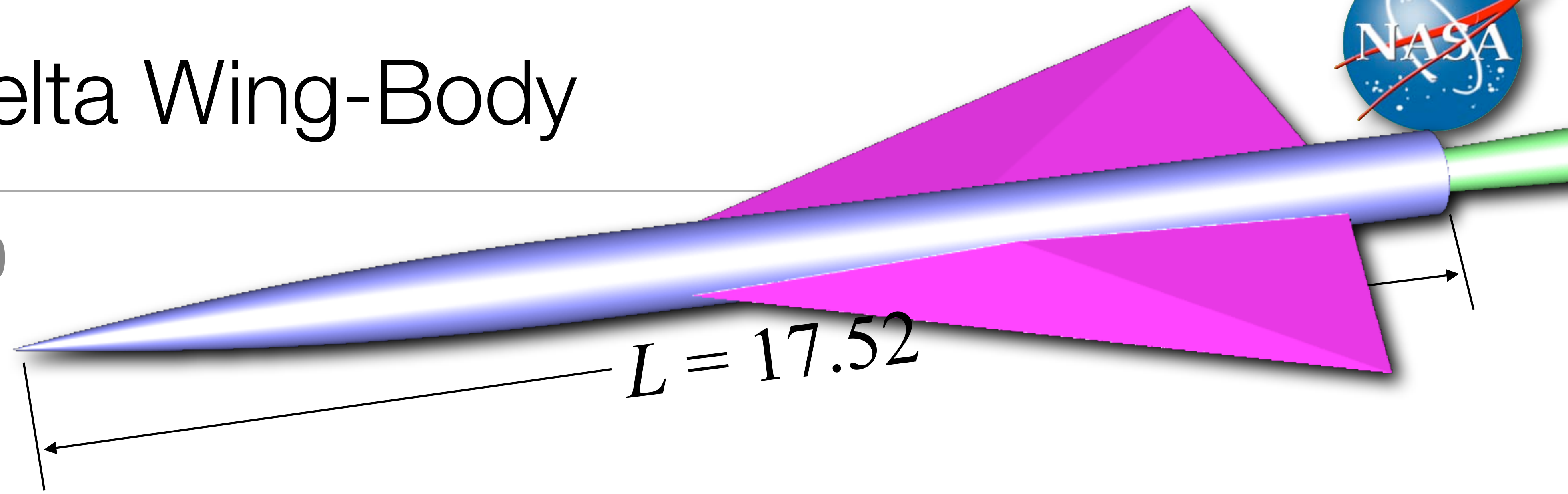
- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$

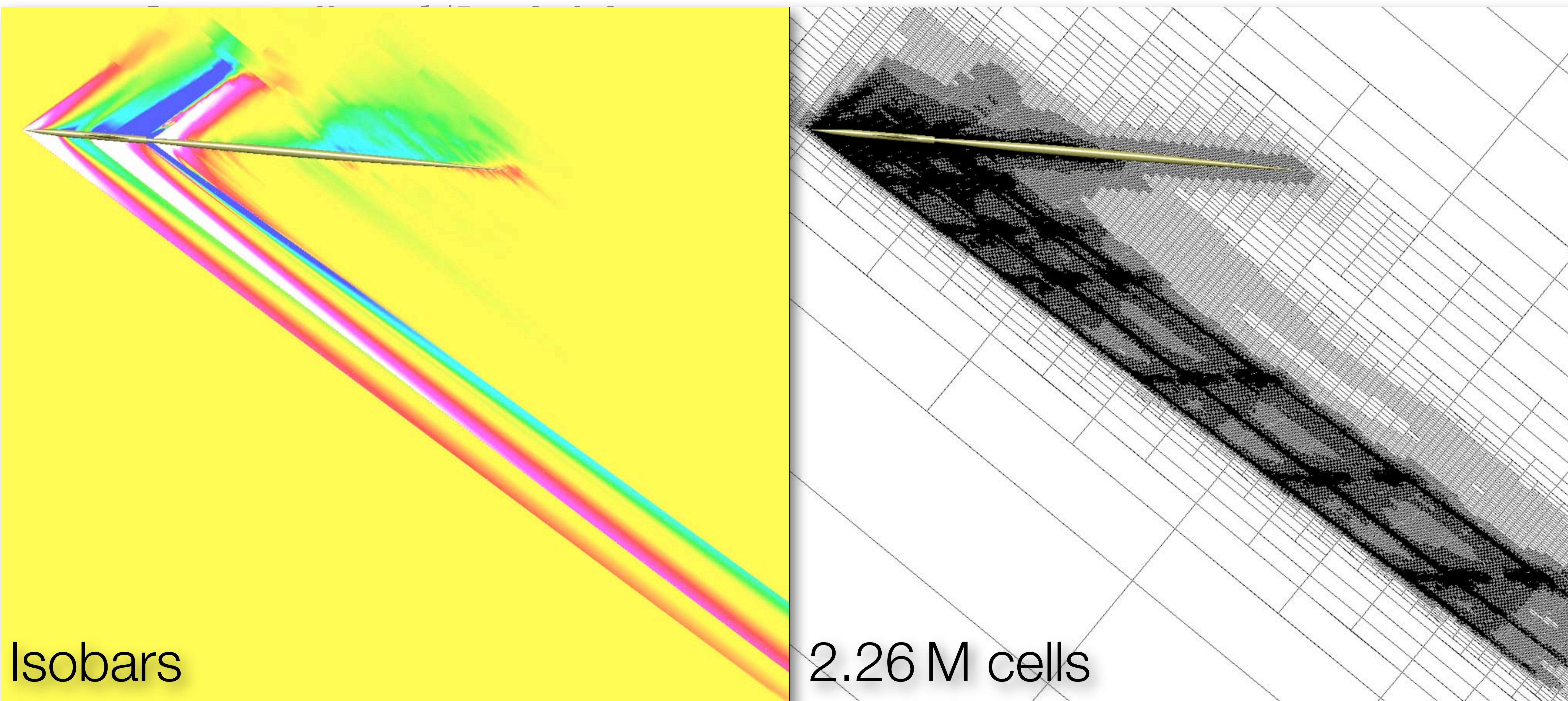




69° Swept Delta Wing-Body

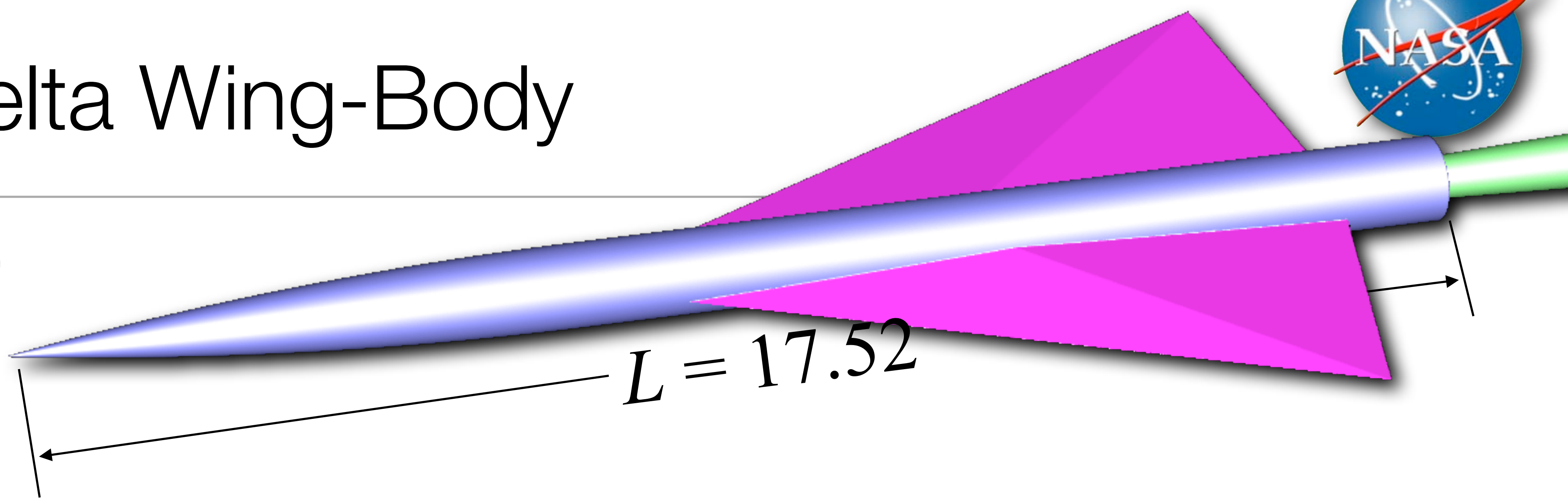
- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$

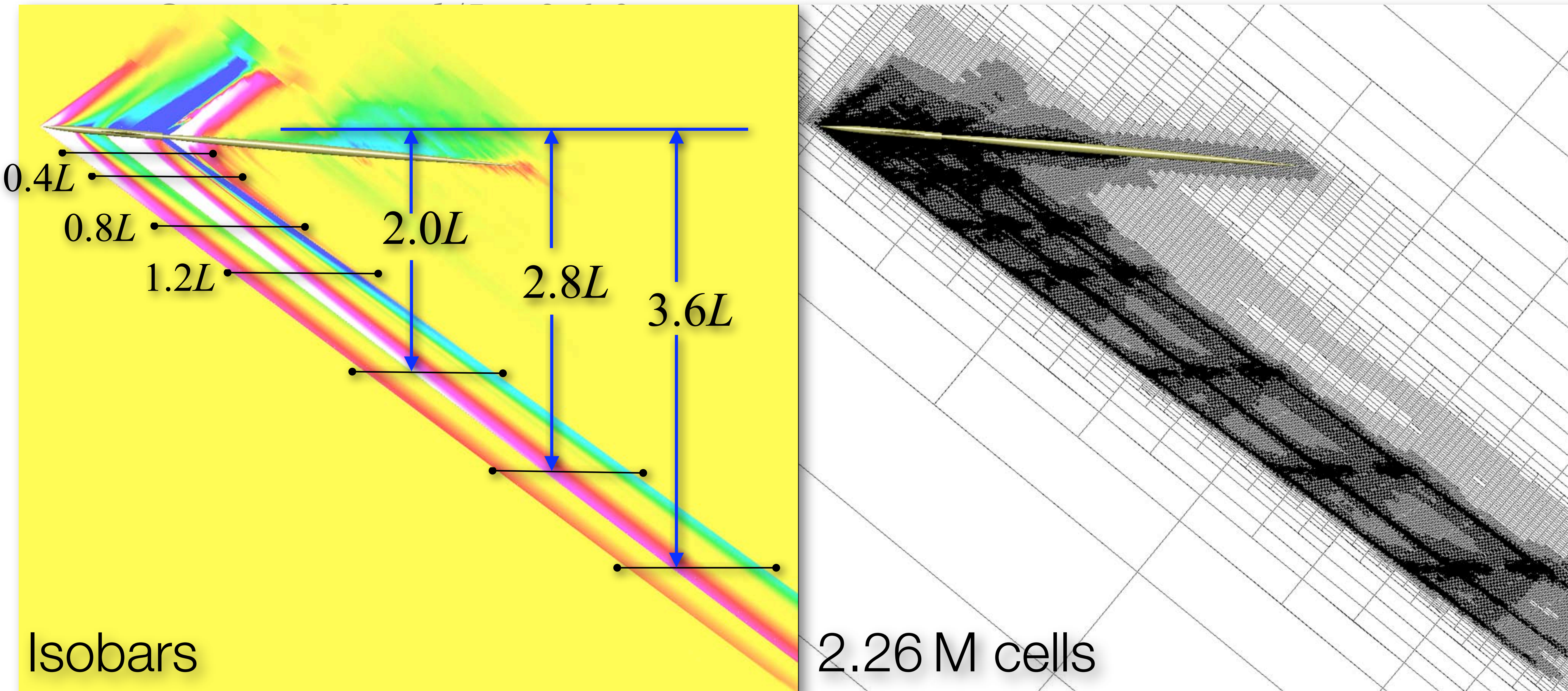




69° Swept Delta Wing-Body

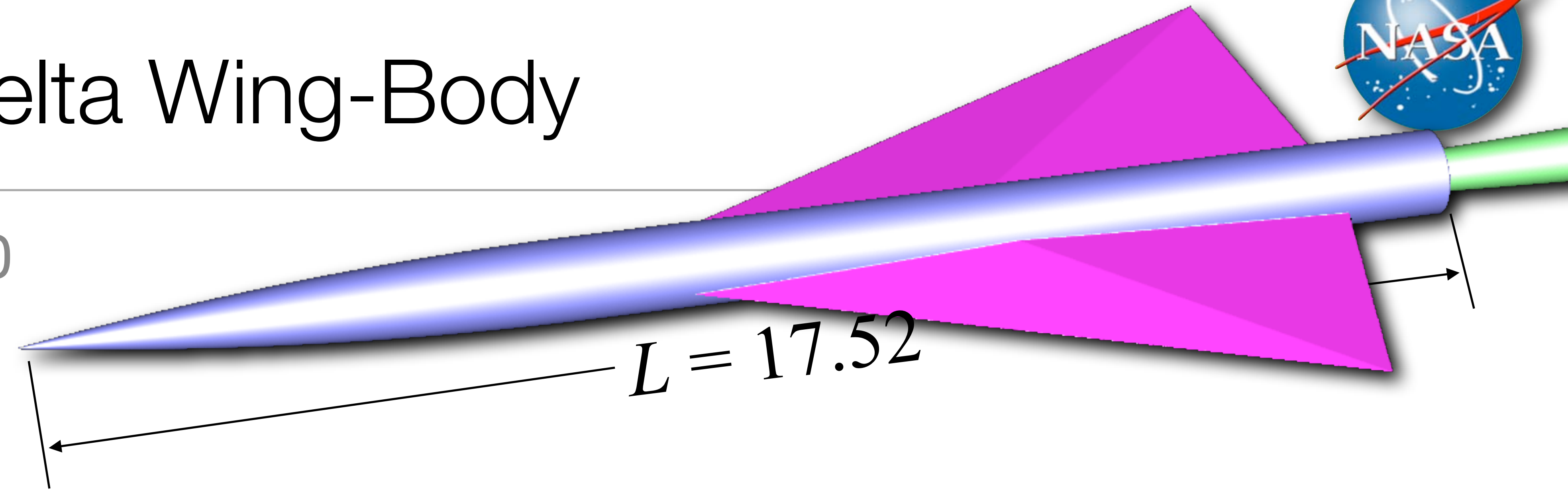
- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$

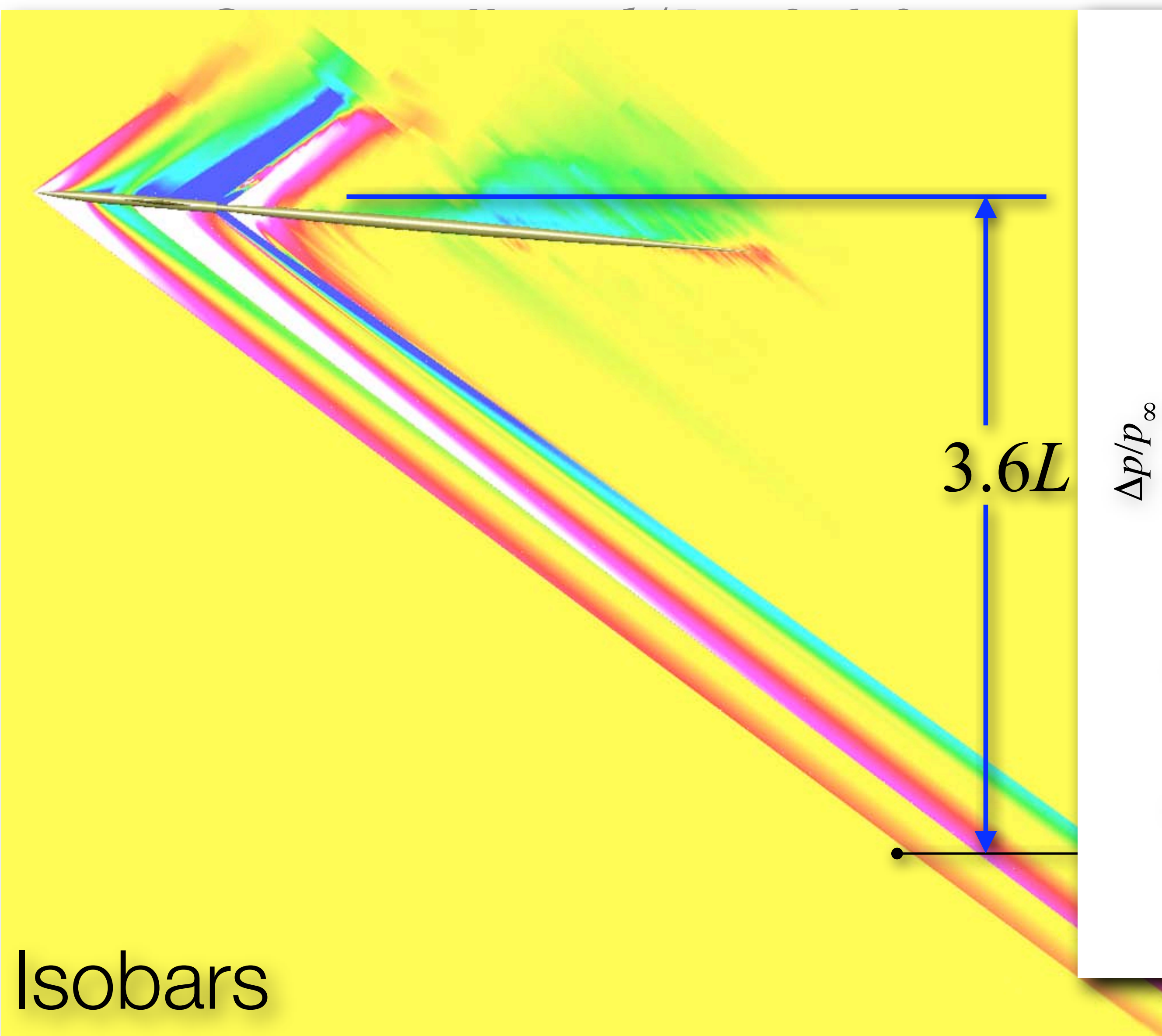


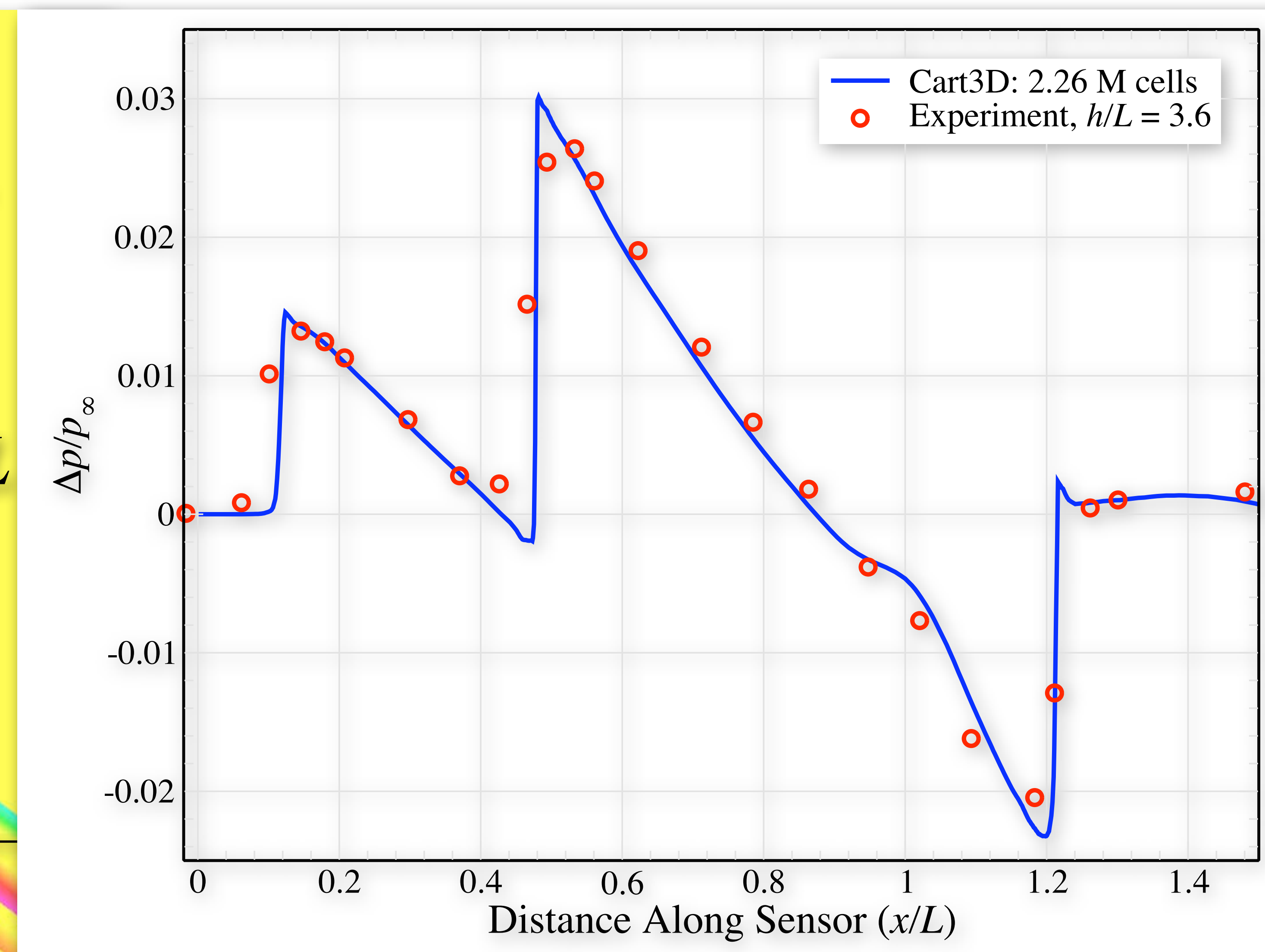


69° Swept Delta Wing-Body

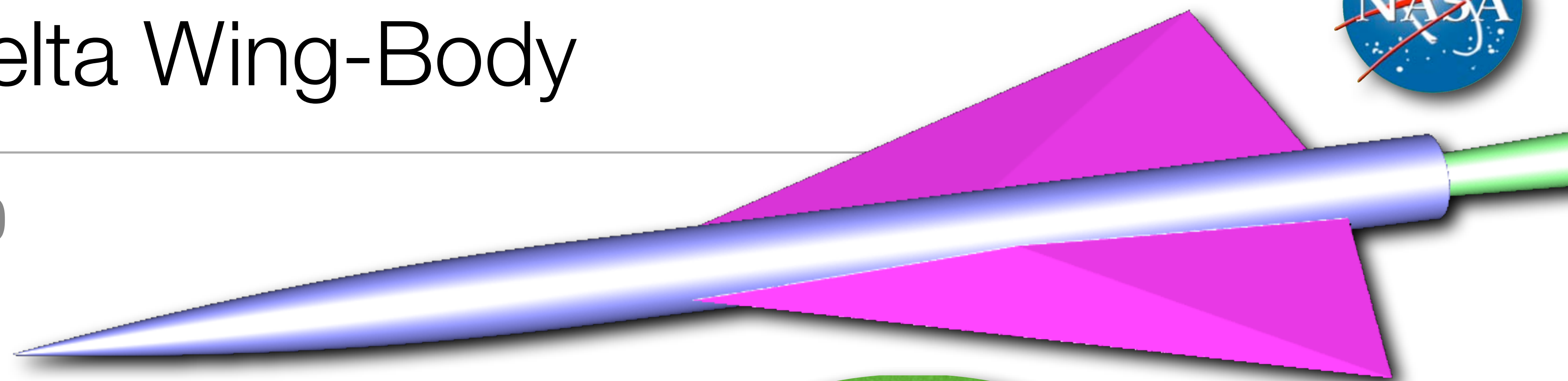
- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$



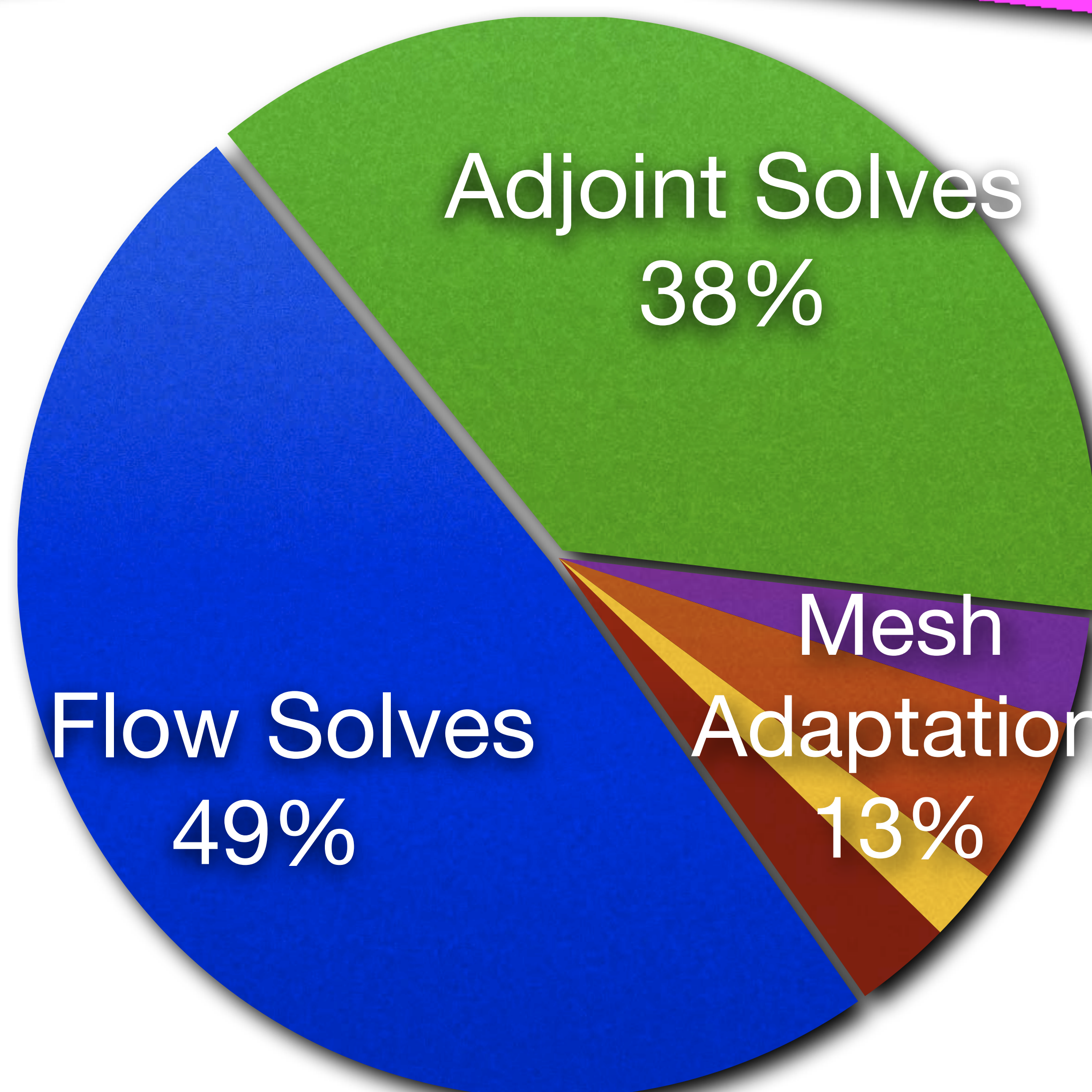




69° Swept Delta Wing-Body



- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74°$
  - $h/L = \{.2, .4, .8, 1.2, 2.0, 2.8, 3.6\}$
- Simulation performed on desktop workstation
  - Dual quad-core (8 cores)
  - Intel Xeon, 3.2Ghz
  - 16 Gb memory
- Total simulation time 53 mins. (all adaptations & mesh gen)



Total = 53 mins.

Results
Focus on Applications

Part A. Accuracy

- Launch Abort Vehicle with jets - uniform mesh refinement study

Part B. Efficiency

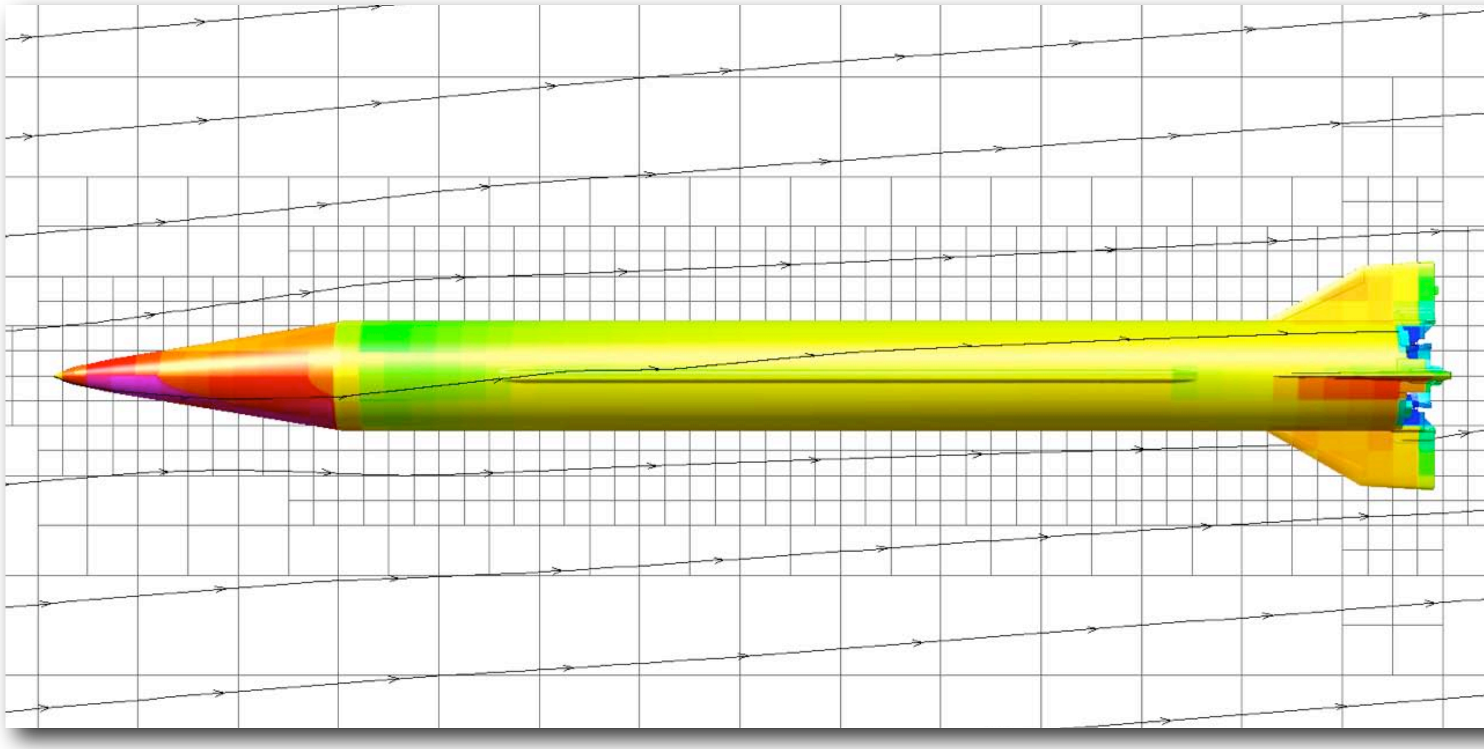
- Sonic-boom signature test case - computational cost summary

Part C. Databases

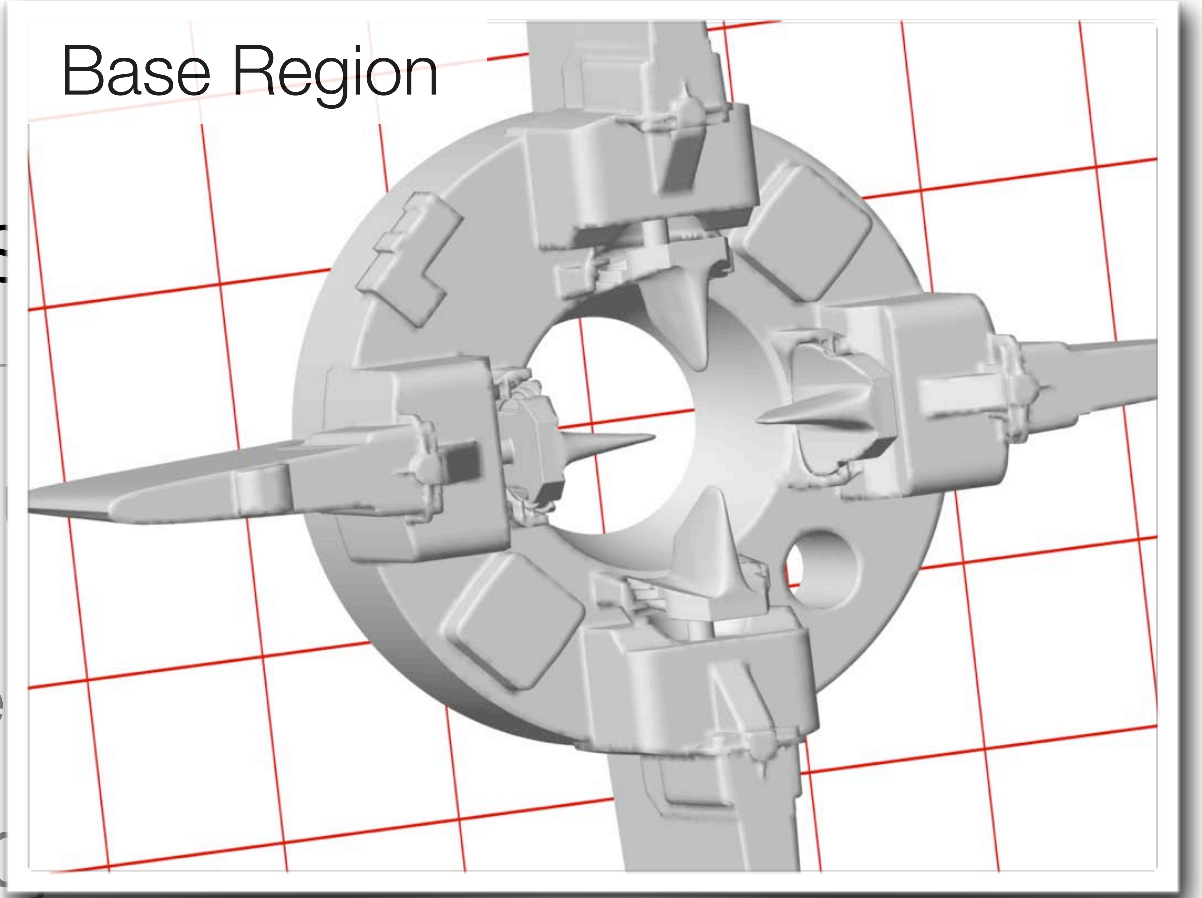
- Nozzle-Guide-Vane Missile
- Launch Abort Vehicle with Jettison Motor plumes

Error Controlled Aero Database

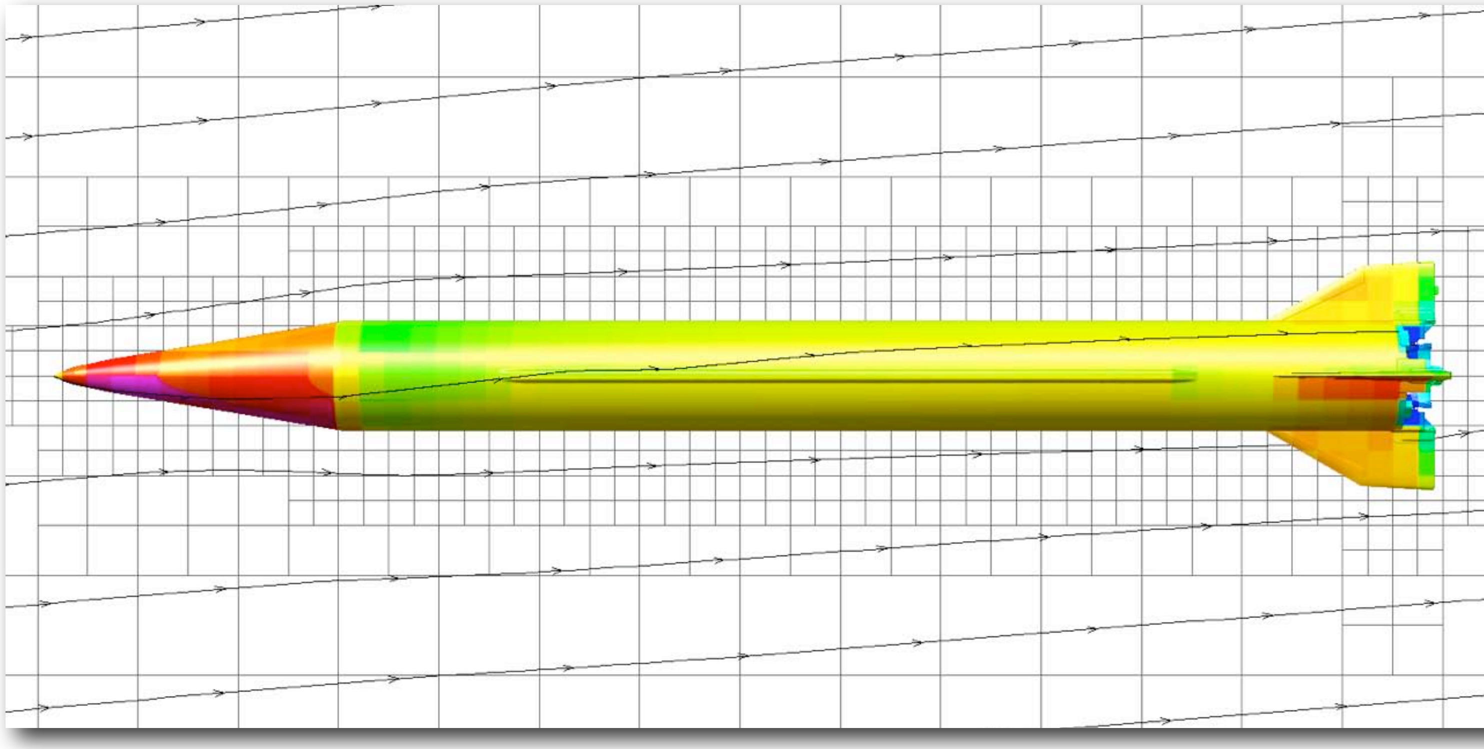
- Realistically complex model with plenum, guide vanes, etc.
- Perform (data blind) aero analysis over range of operating conditions
  - $M_\infty = \{0.5, 0.7, 0.9, 1.1, 1.3, 1.6, 2.0\}$
  - $\alpha = \{0°, 5°, 10°, 15°, 20°\}$ = 35 cases total
  - Output functional: $J = C_N + 0.1C_A$, TOL = 0.05
- Starting mesh has ~8000 cells



Error Controlled Aero Databas

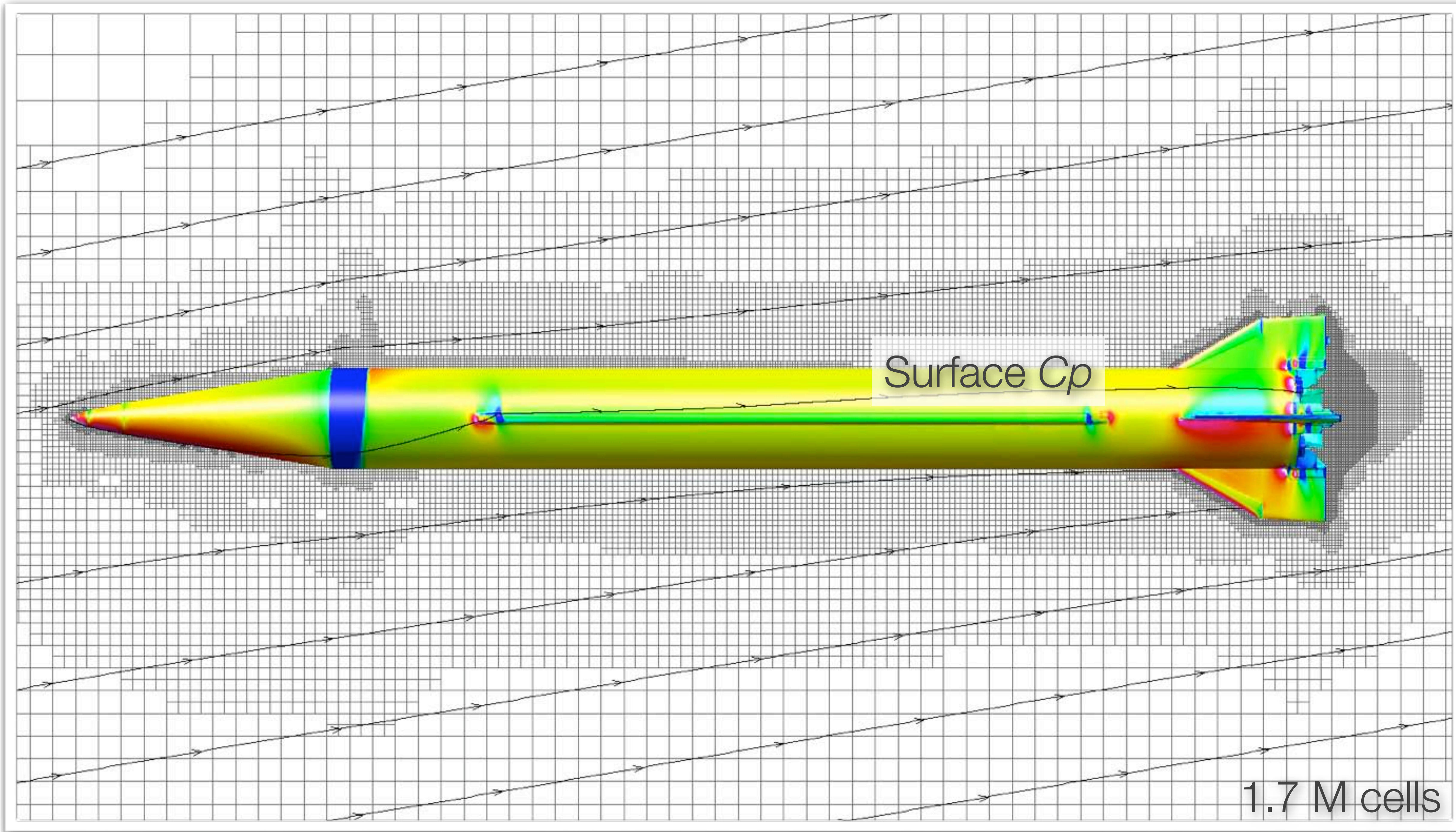


- Realistically complex model with plen
- Perform (data blind) aero analysis ove
  - M_∞ = {0.5, 0.7, 0.9, 1.1, 1.3, 1.6, 2.0
  - α = {0°, 5°, 10°, 15°, 20°} = 35 cases total
  - Output functional: $J = C_N + 0.1C_A$, TOL = 0.05
- Starting mesh has ~8000 cells



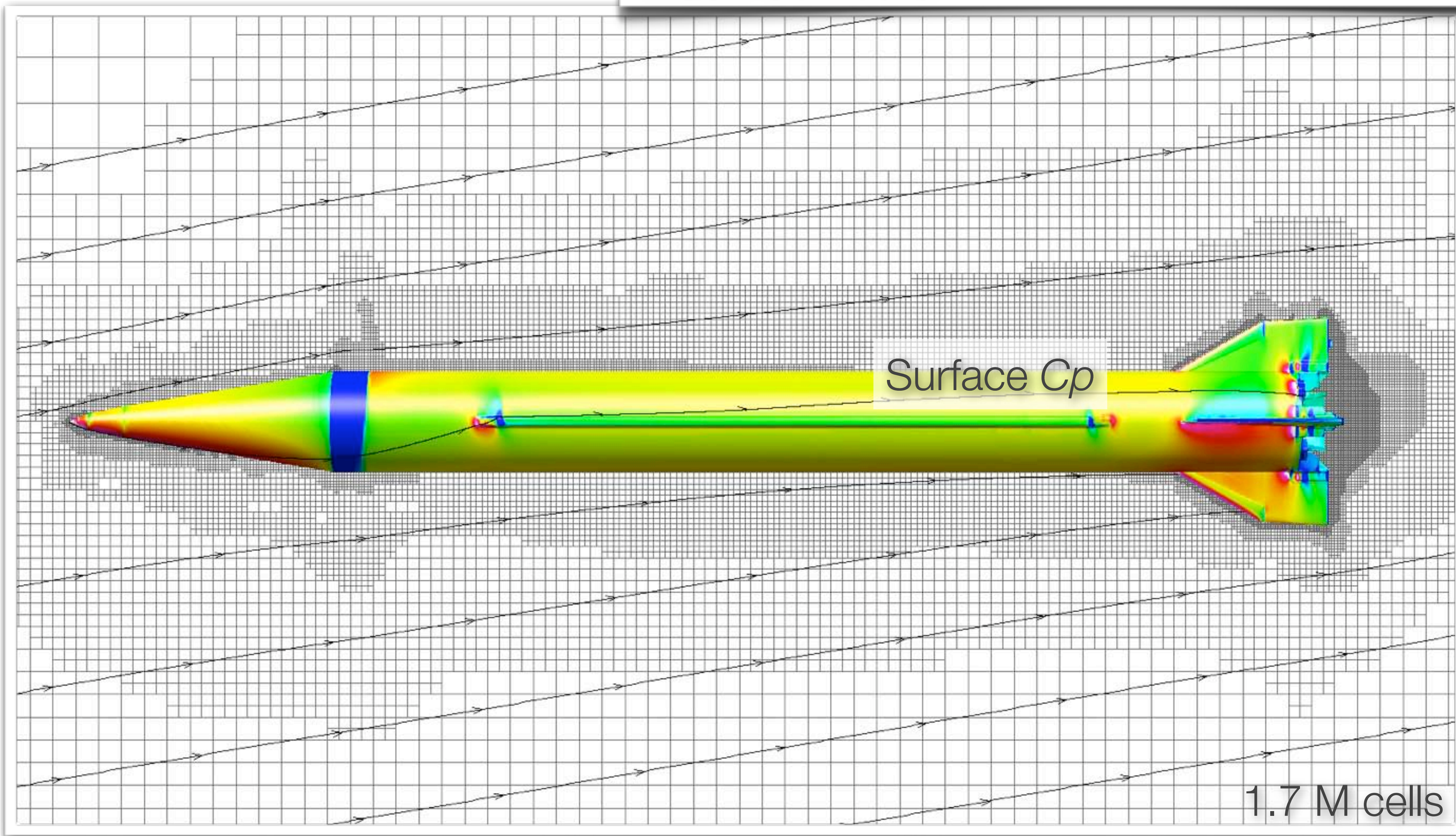
Example Case

$M_\infty = 0.9, \alpha = 10°$



Example Case

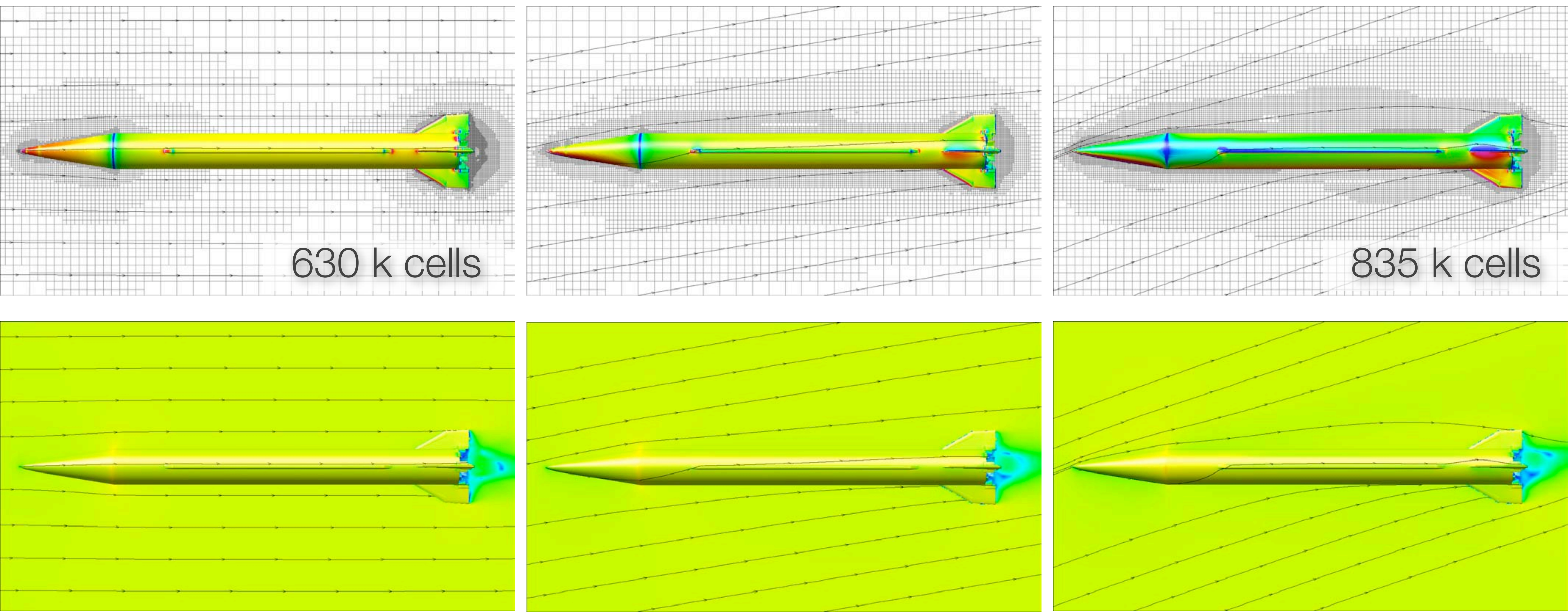
$M_\infty = 0.9,\ \alpha = 10°$



Error Controlled Aero Database

$M_\infty = 0.5$

$\alpha = 0°$ $\alpha = 10°$ $\alpha = 20°$

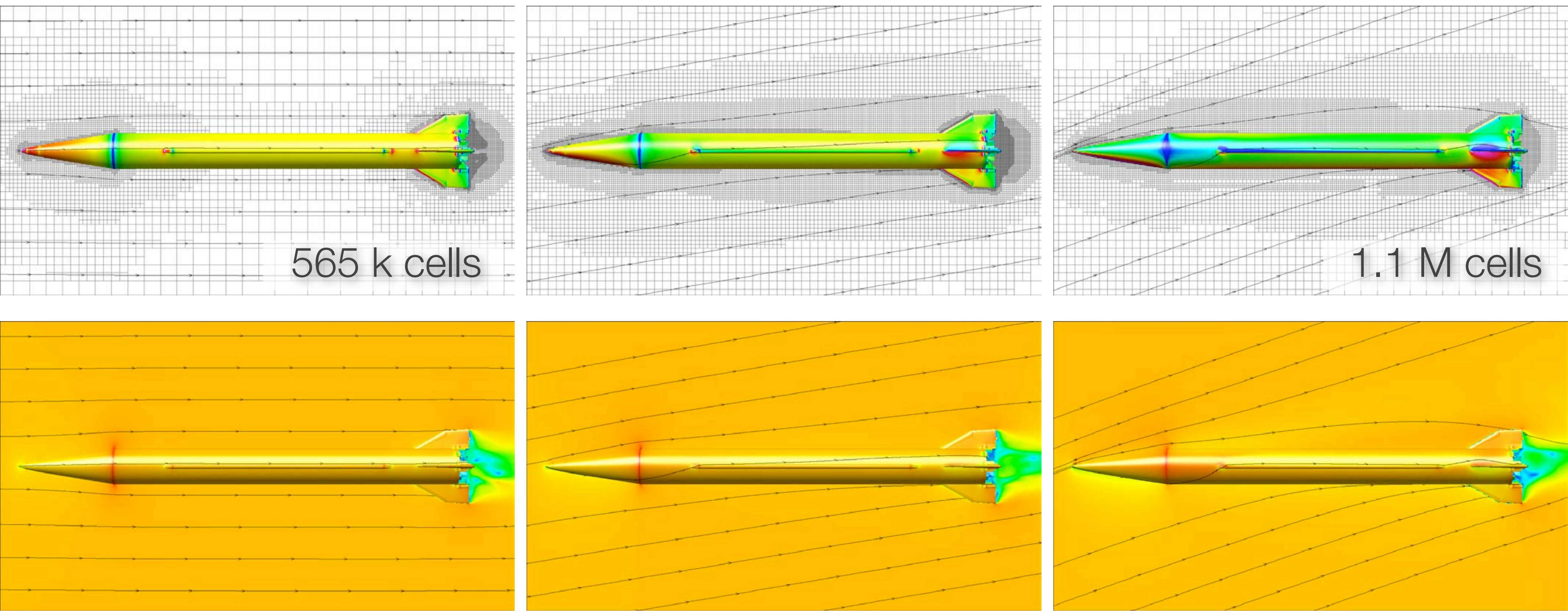


Mach Contours

Error Controlled Aero Database

$M_\infty = 0.7$

$\alpha = 0°$ $\alpha = 10°$ $\alpha = 20°$

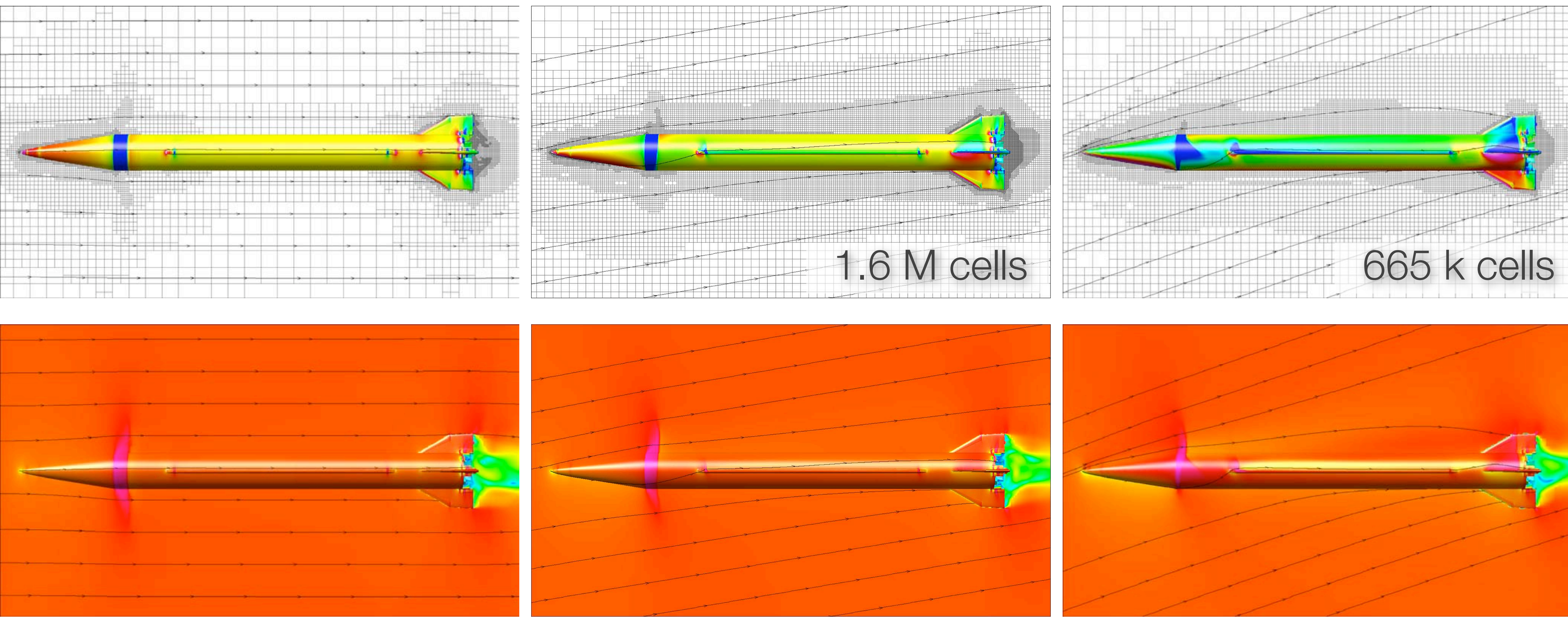


Mach Contours

Error Controlled Aero Database

$M_\infty = 0.9$

$\alpha = 0°$ $\alpha = 10°$ $\alpha = 20°$

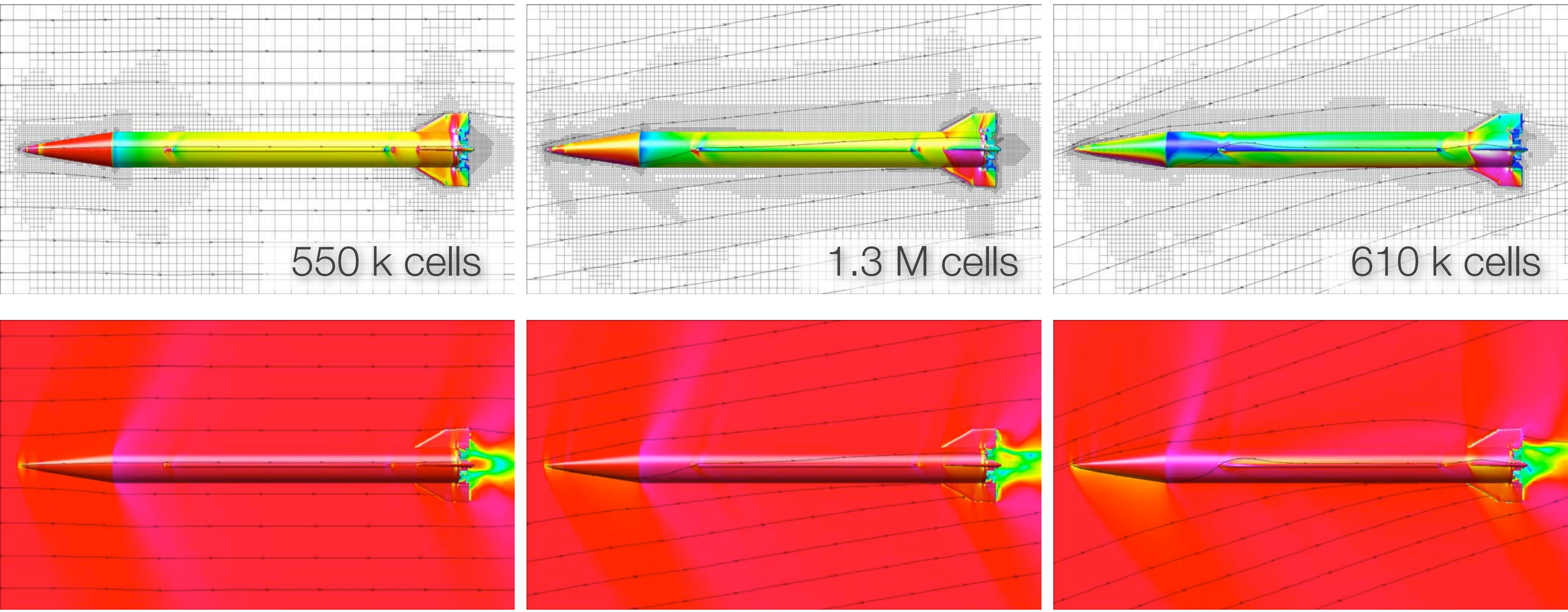


Mach Contours

Error Controlled Aero Database

$M_\infty = 1.1$

$\alpha = 0°$ $\alpha = 10°$ $\alpha = 20°$

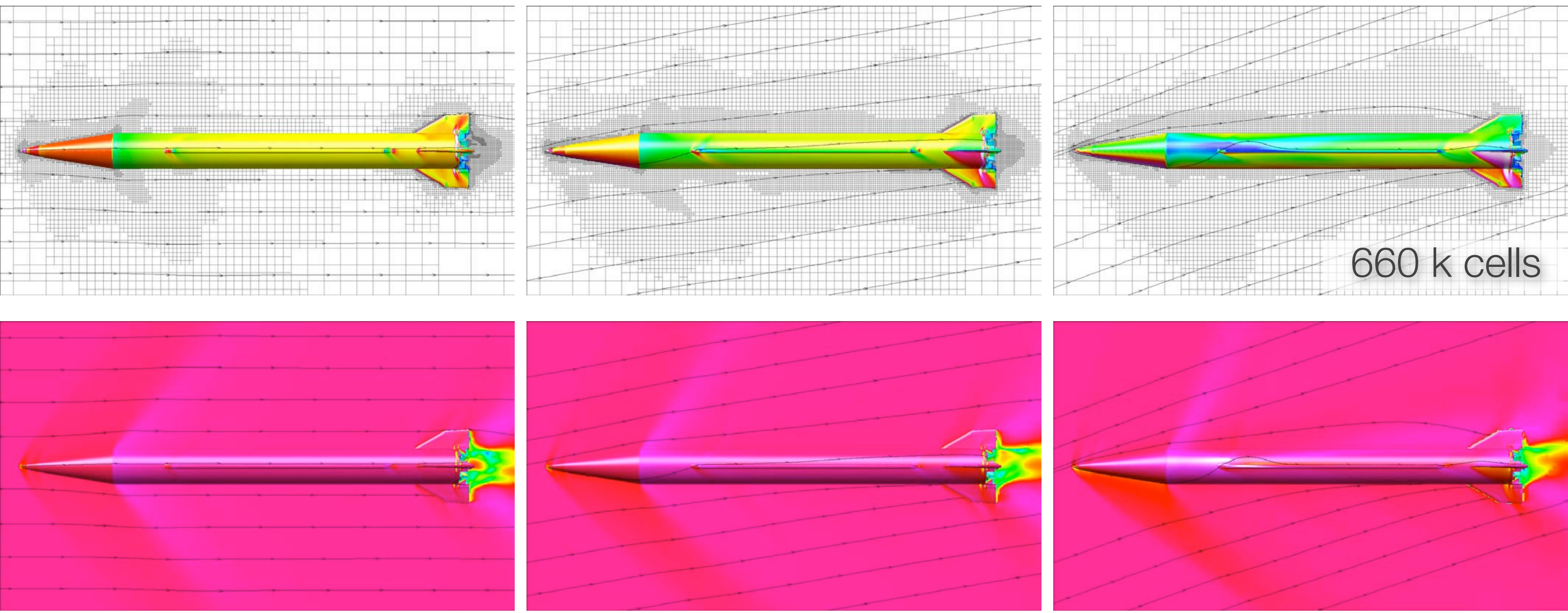


Mach Contours

Error Controlled Aero Database

$M_\infty = 1.3$

$\alpha = 0°$ $\alpha = 10°$ $\alpha = 20°$

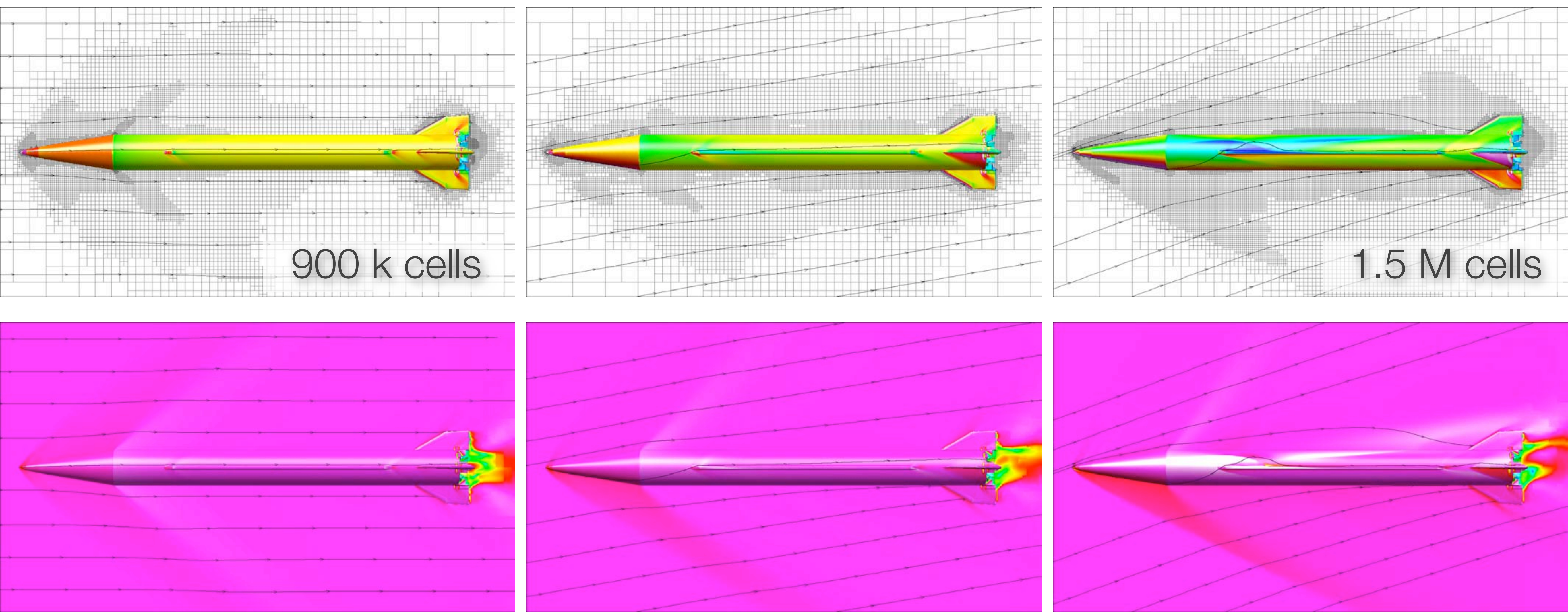


Mach Contours

Error Controlled Aero Database

$M_\infty = 1.6$

$\alpha = 0°$ $\alpha = 10°$ $\alpha = 20°$

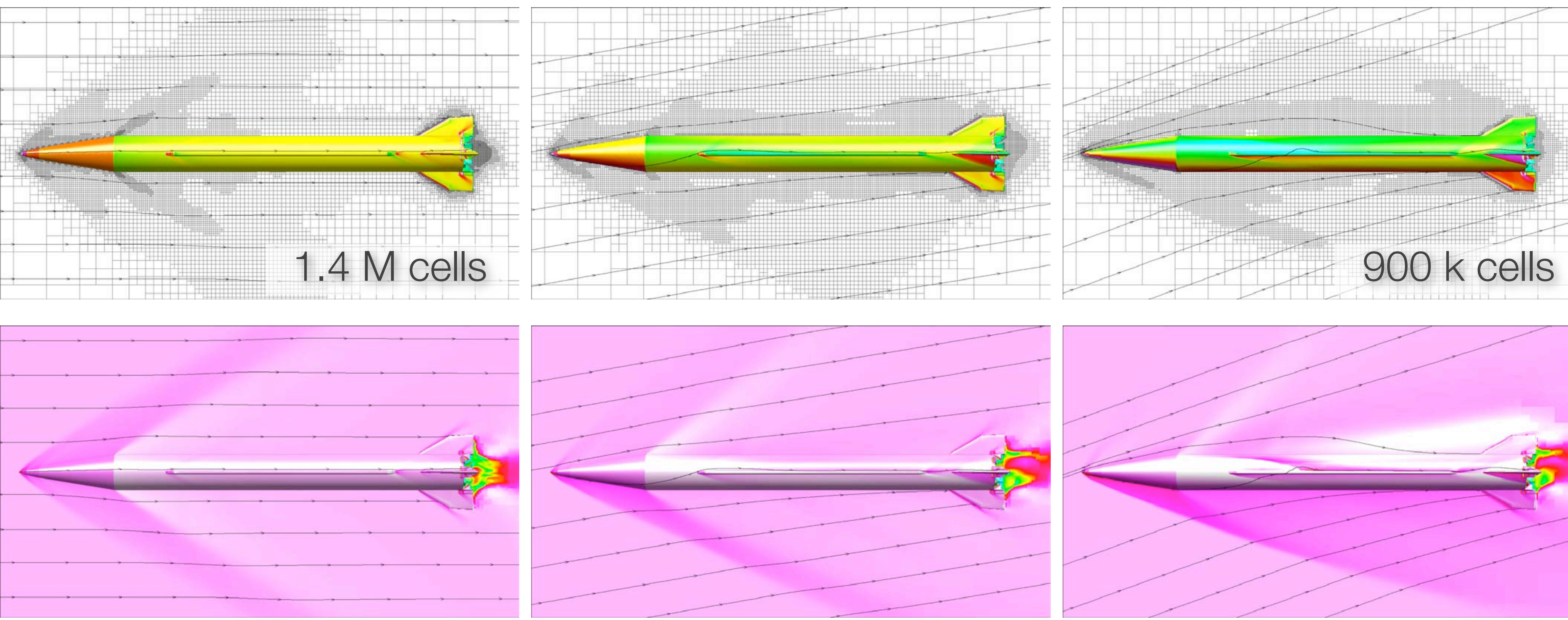


Mach Contours

Error Controlled Aero Database

$M_\infty = 2.0$

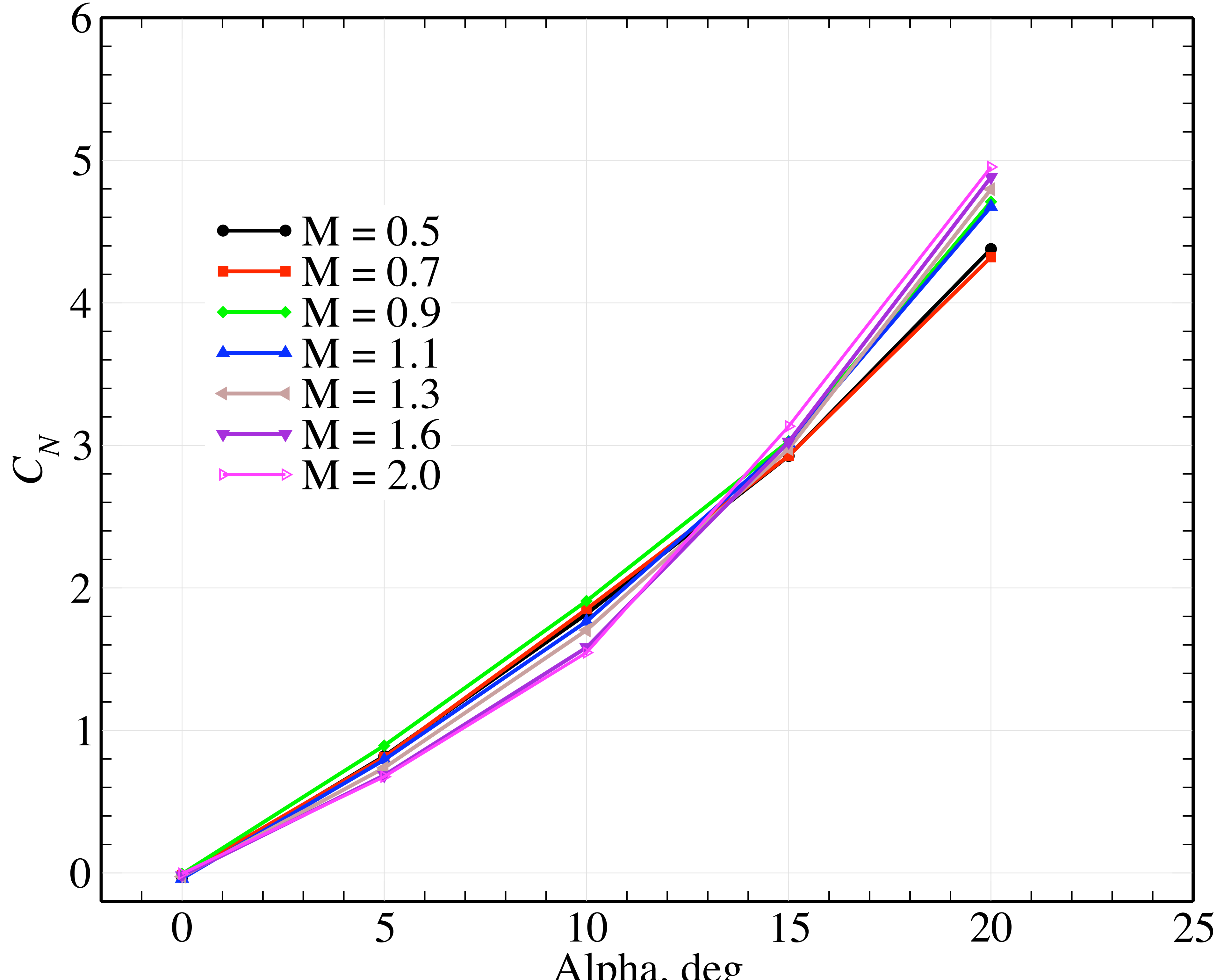
$\alpha = 0°$ $\alpha = 10°$ $\alpha = 20°$



Mach Contours

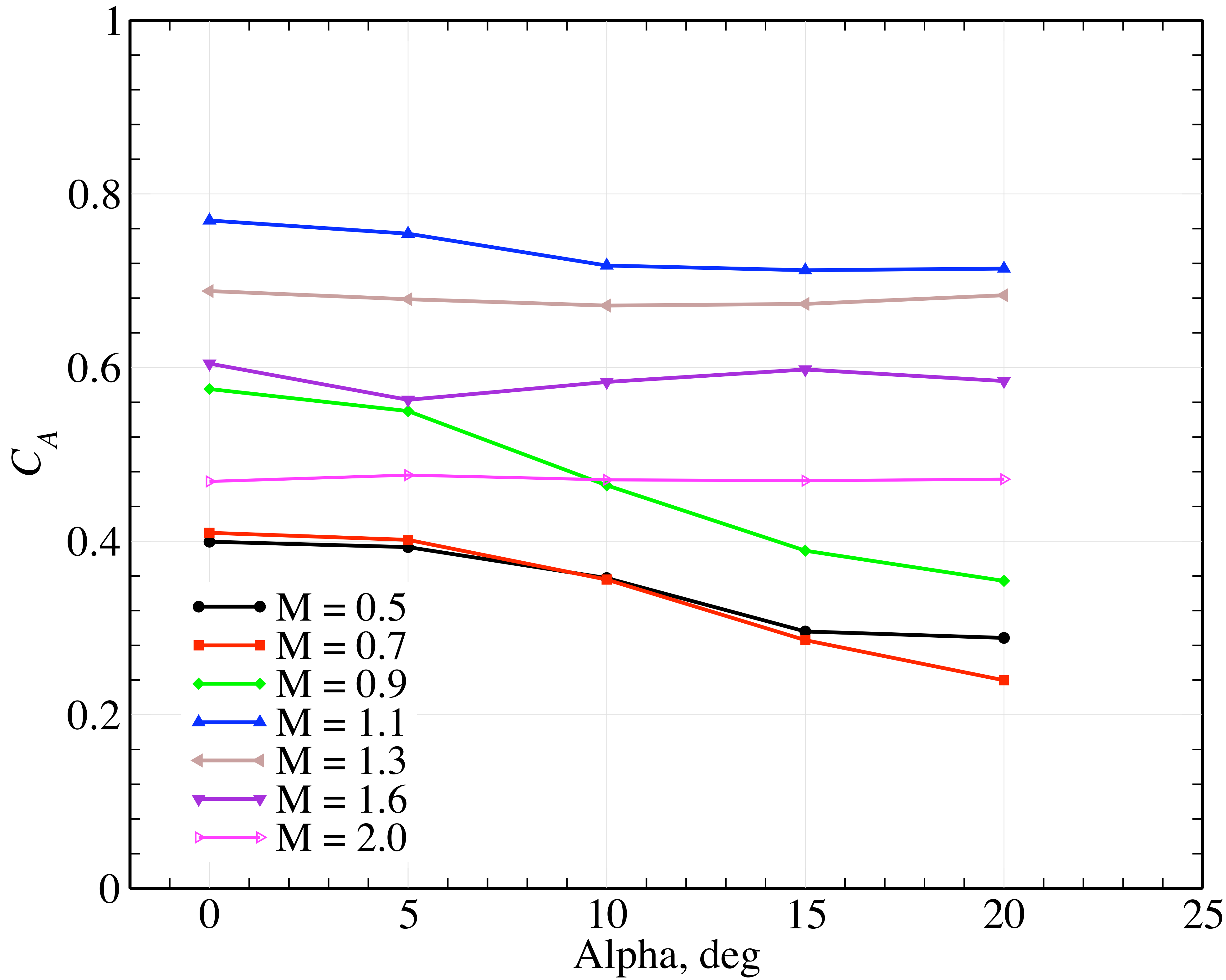
Error Controlled Aero Database

Normal Force Coefficient



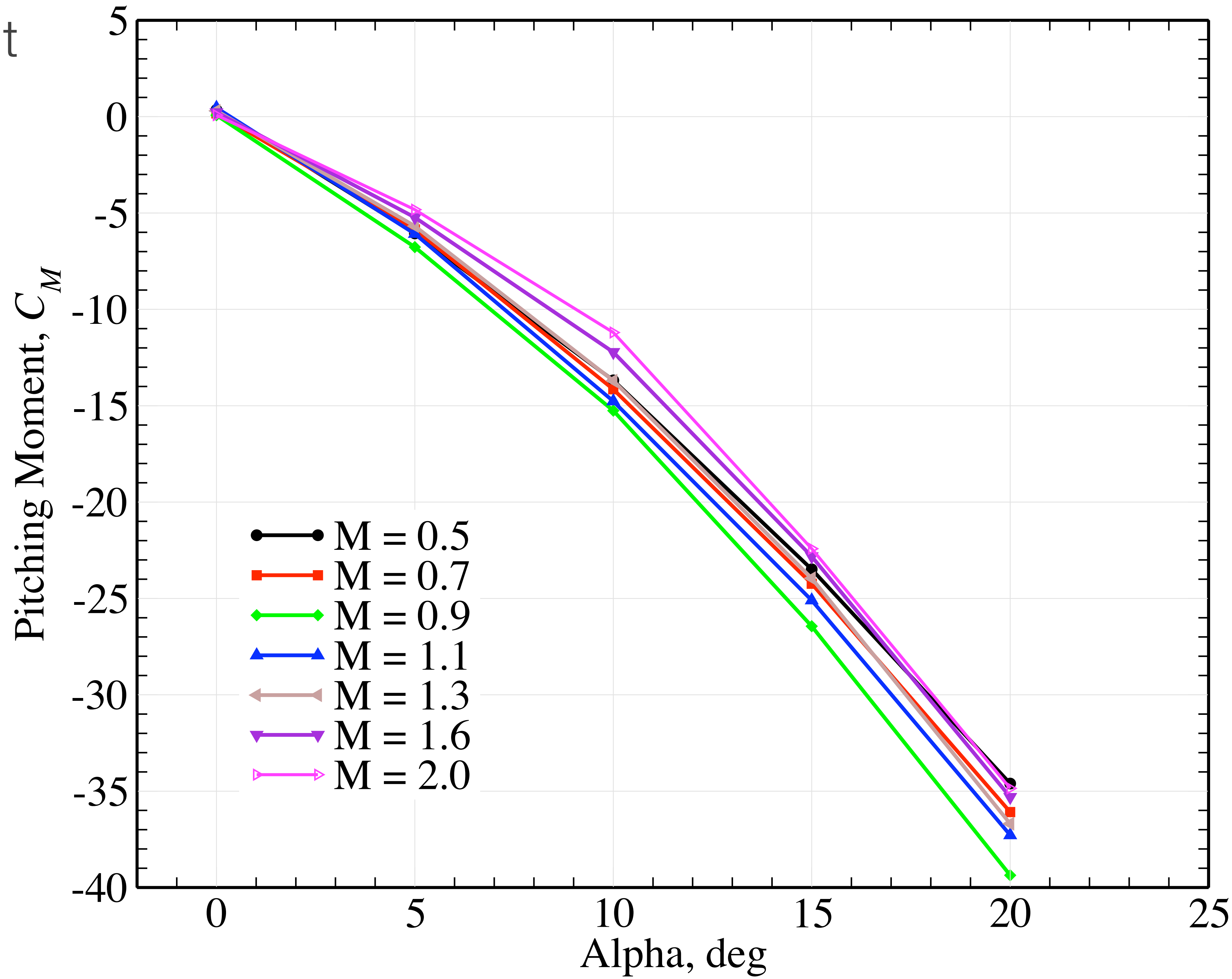
Error Controlled Aero Database

Axial Force Coefficient



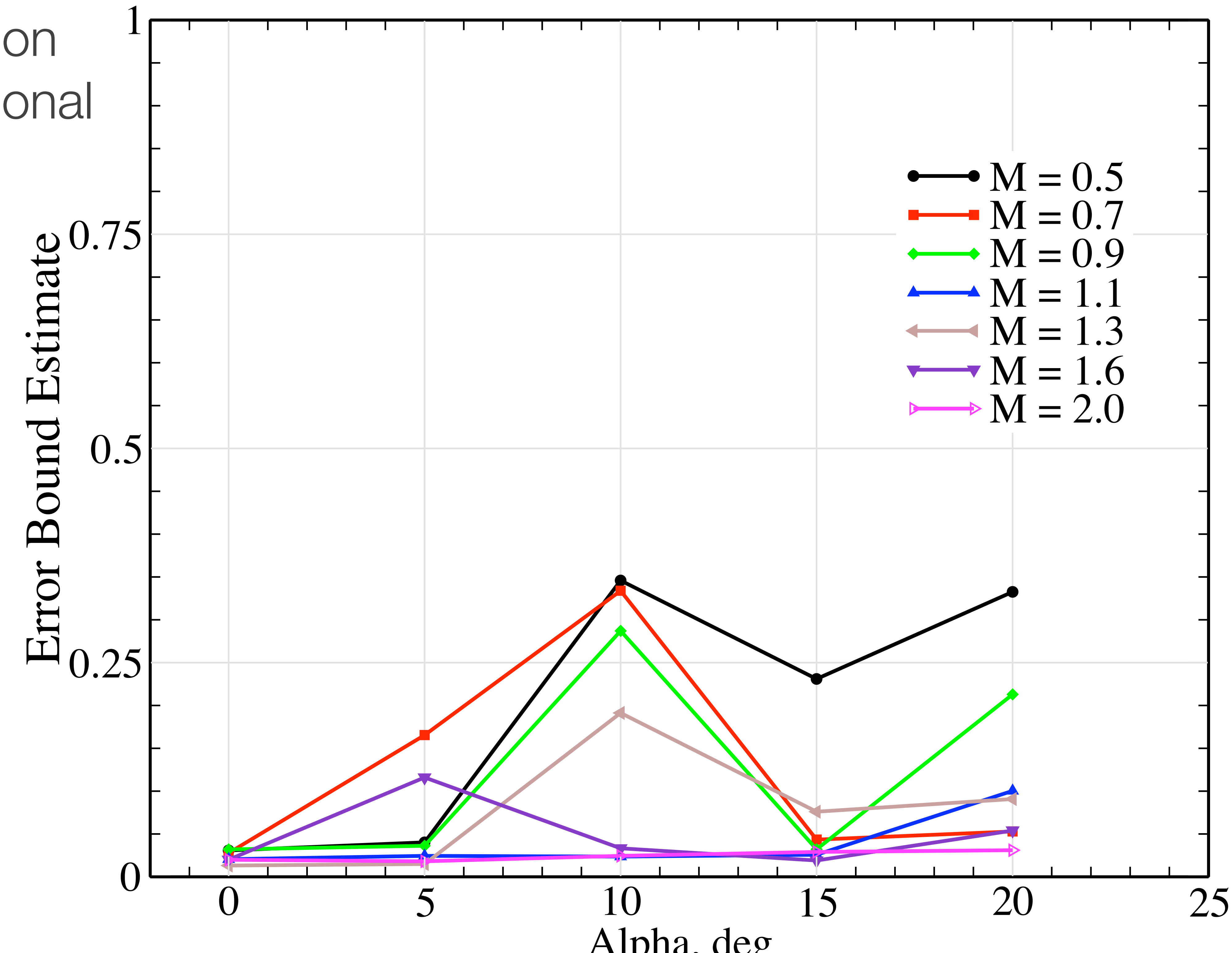
Error Controlled Aero Database

Pitch moment about nose



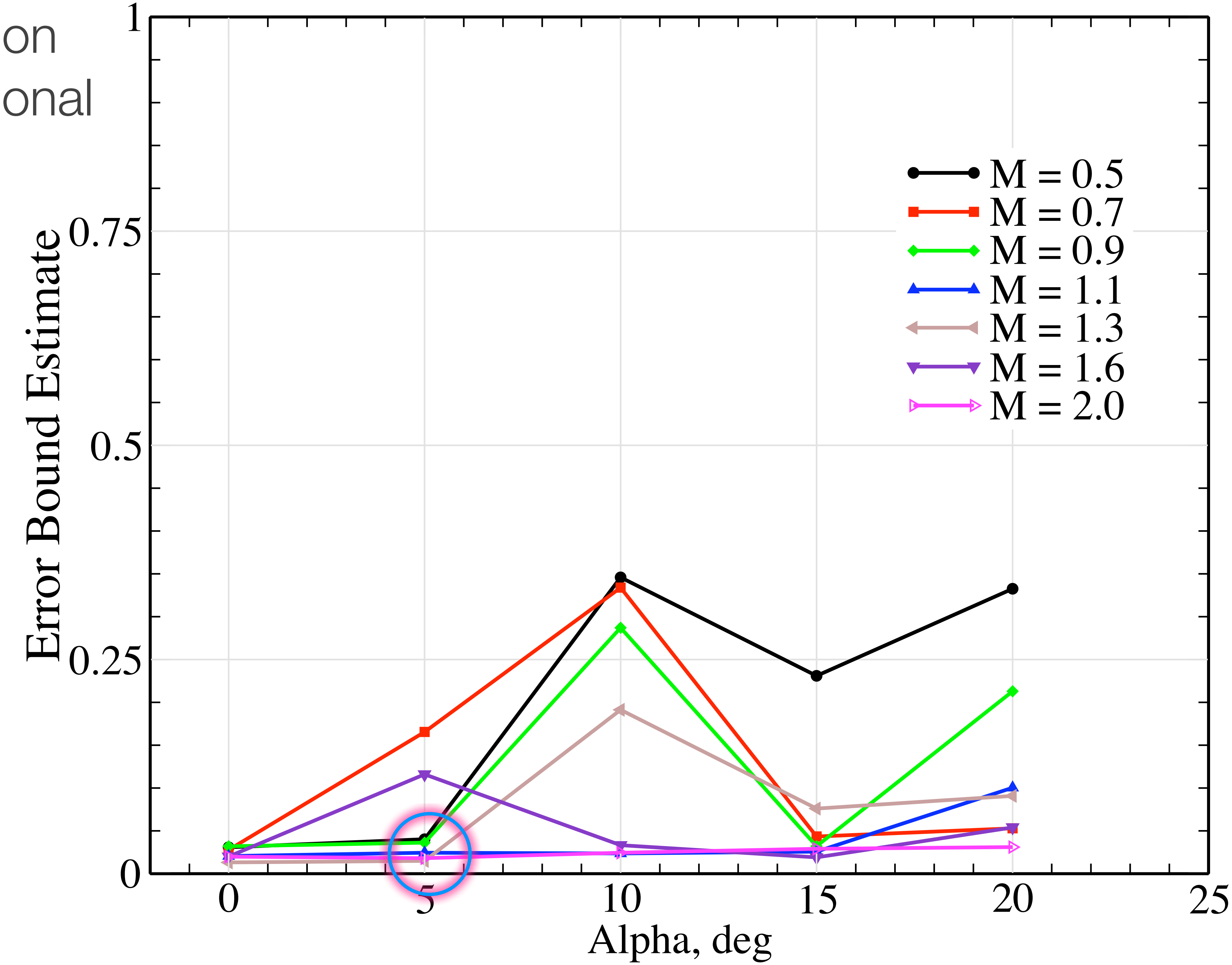
Error Controlled Aero Database

Error bound on output functional

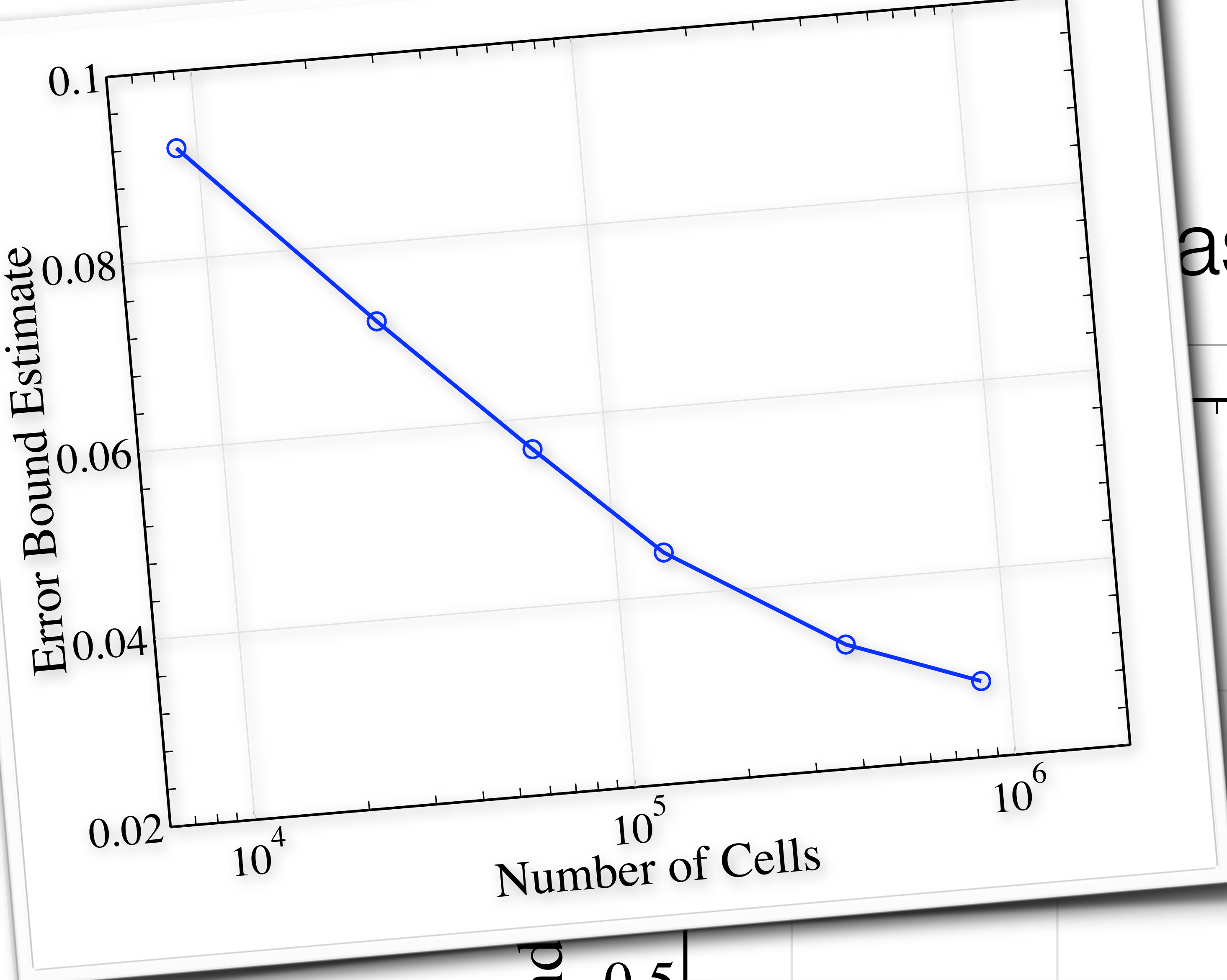


Error Controlled Aero Database

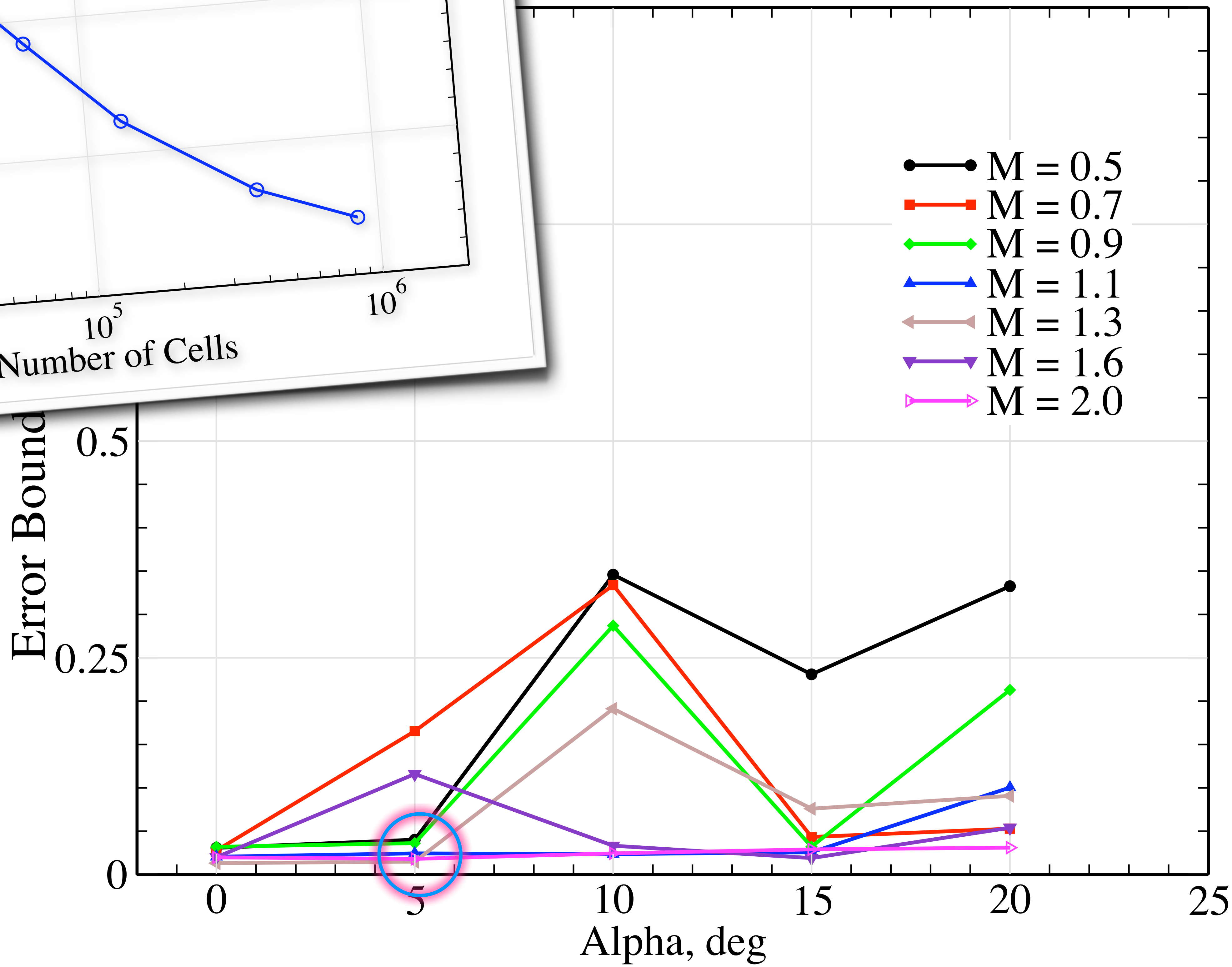
Error bound on output functional



ase

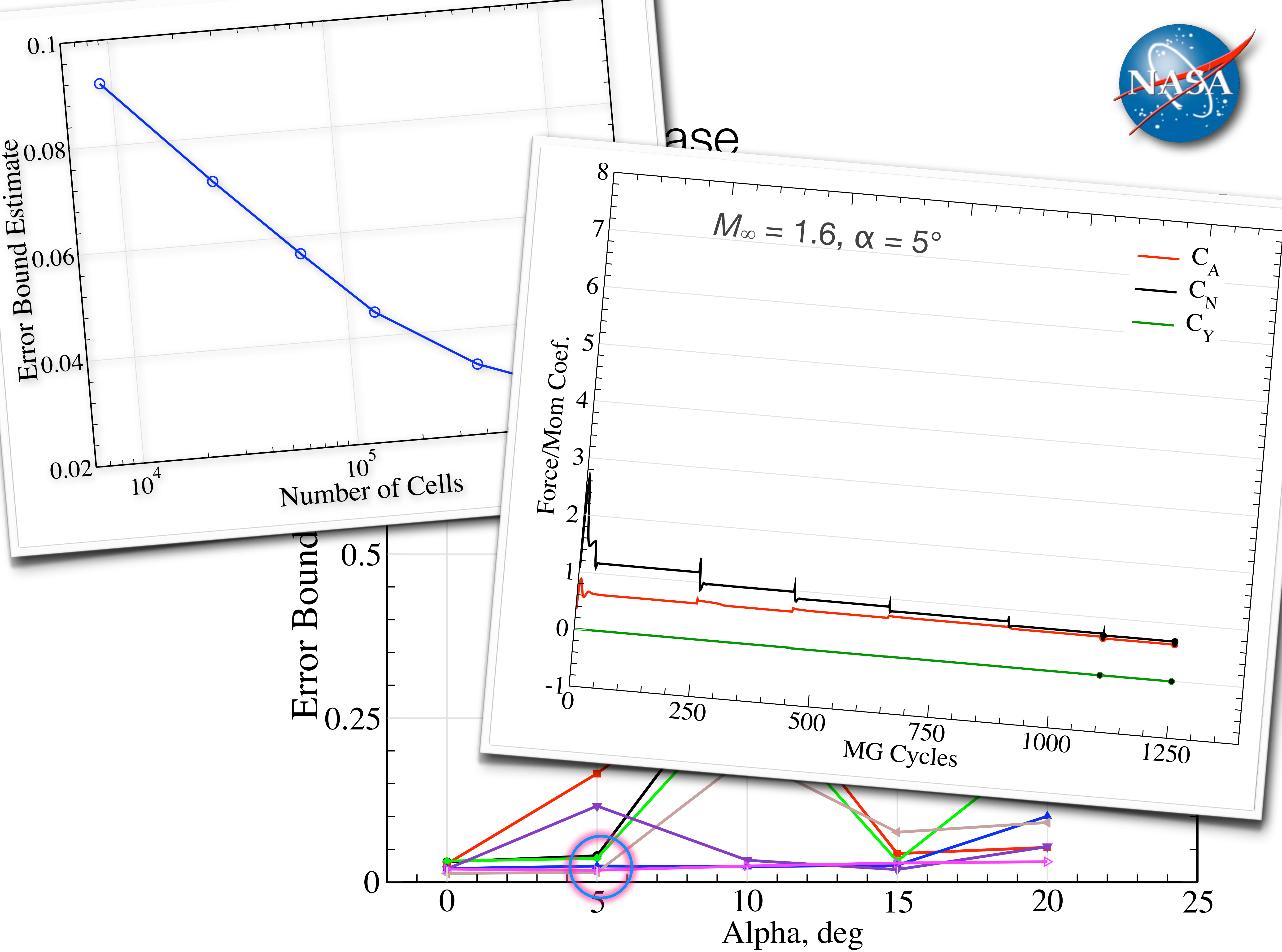


0.1
0.08
0.06
0.04
0.02
Error Bound Estimate
10^4
10^5
10^6
Number of Cells



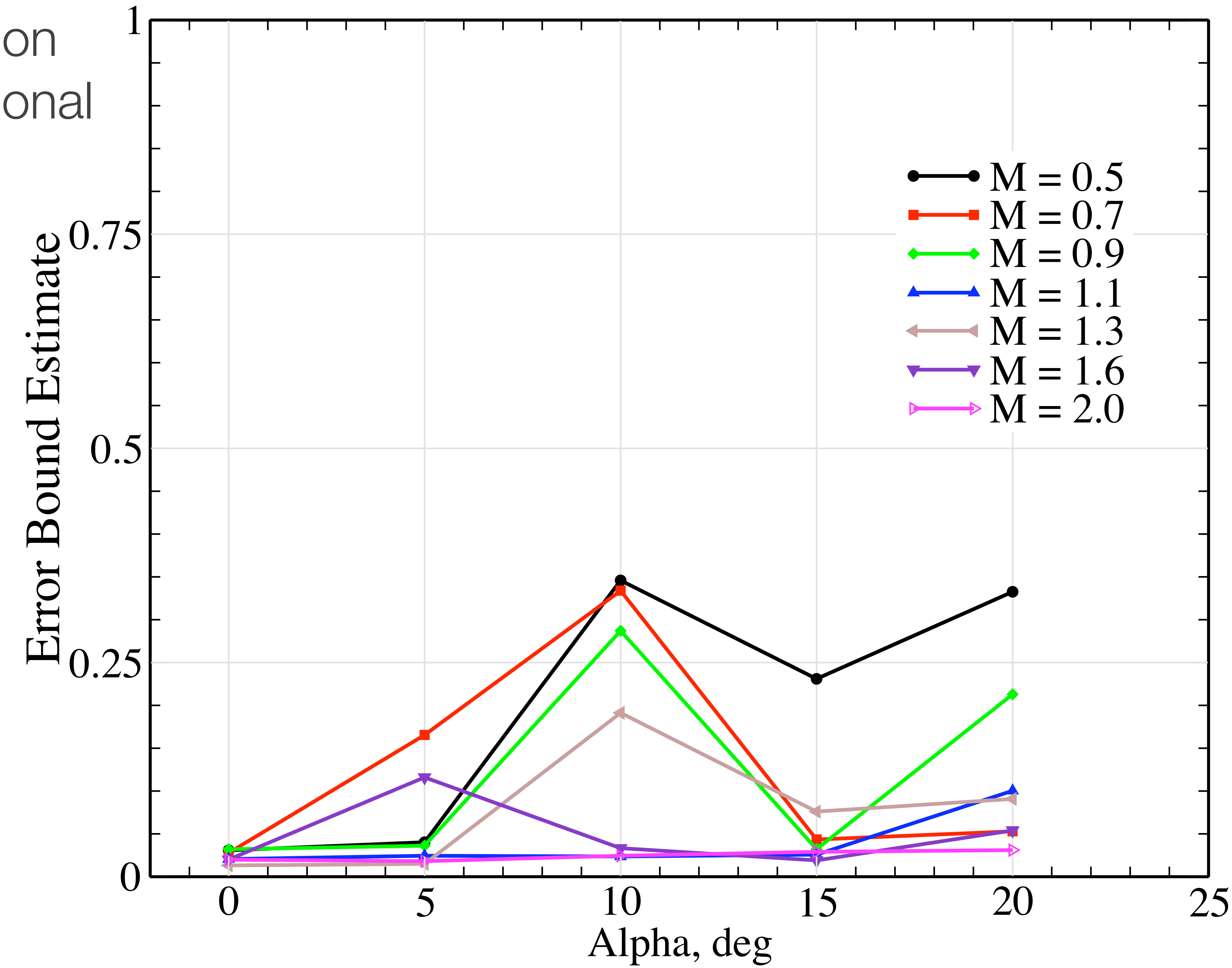
M = 0.5
M = 0.7
M = 0.9
M = 1.1
M = 1.3
M = 1.6
M = 2.0
Error Bound
0.5
0.25
0
0
5
10
15
20
25
Alpha, deg

ase


0.1
0.08
0.06
0.04
0.02
Error Bound Estimate
10^4
10^5
Number of Cells
$M_\infty = 1.6, \alpha = 5°$
C_A
C_N
C_Y
Force/Mom Coef.
8
7
6
5
4
3
2
1
0
-1
0
250
500
750
1000
1250
MG Cycles
Error Bound
0.5
0.25
0
0
5
10
15
20
25
Alpha, deg

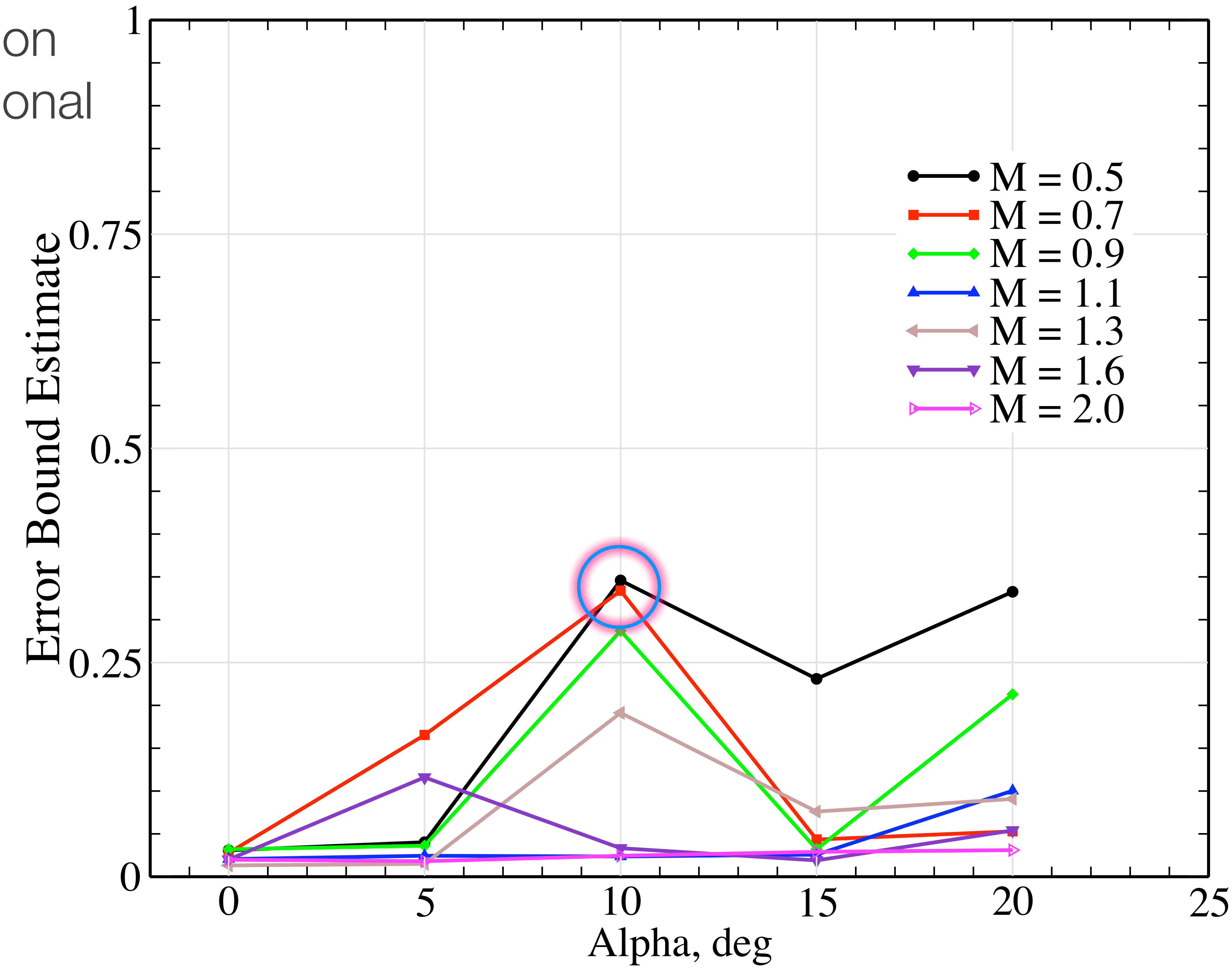
Error Controlled Aero Database

Error bound on output functional

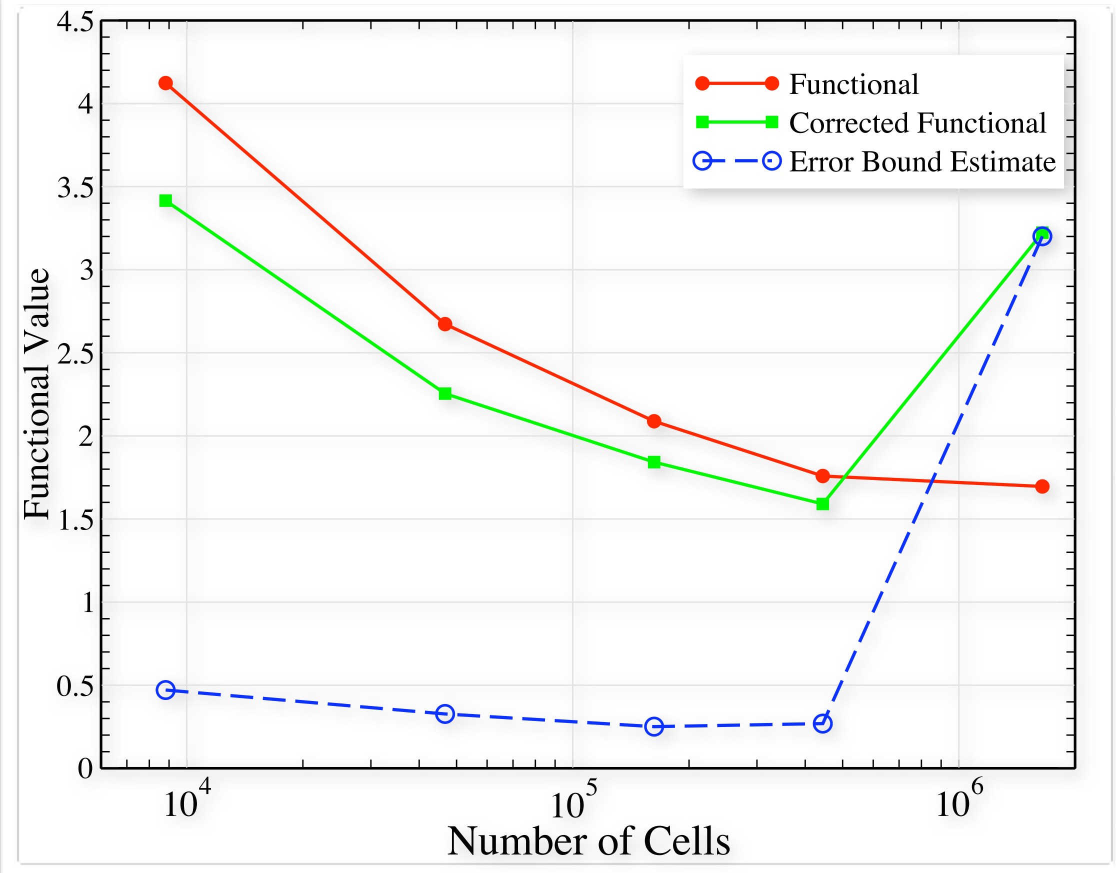


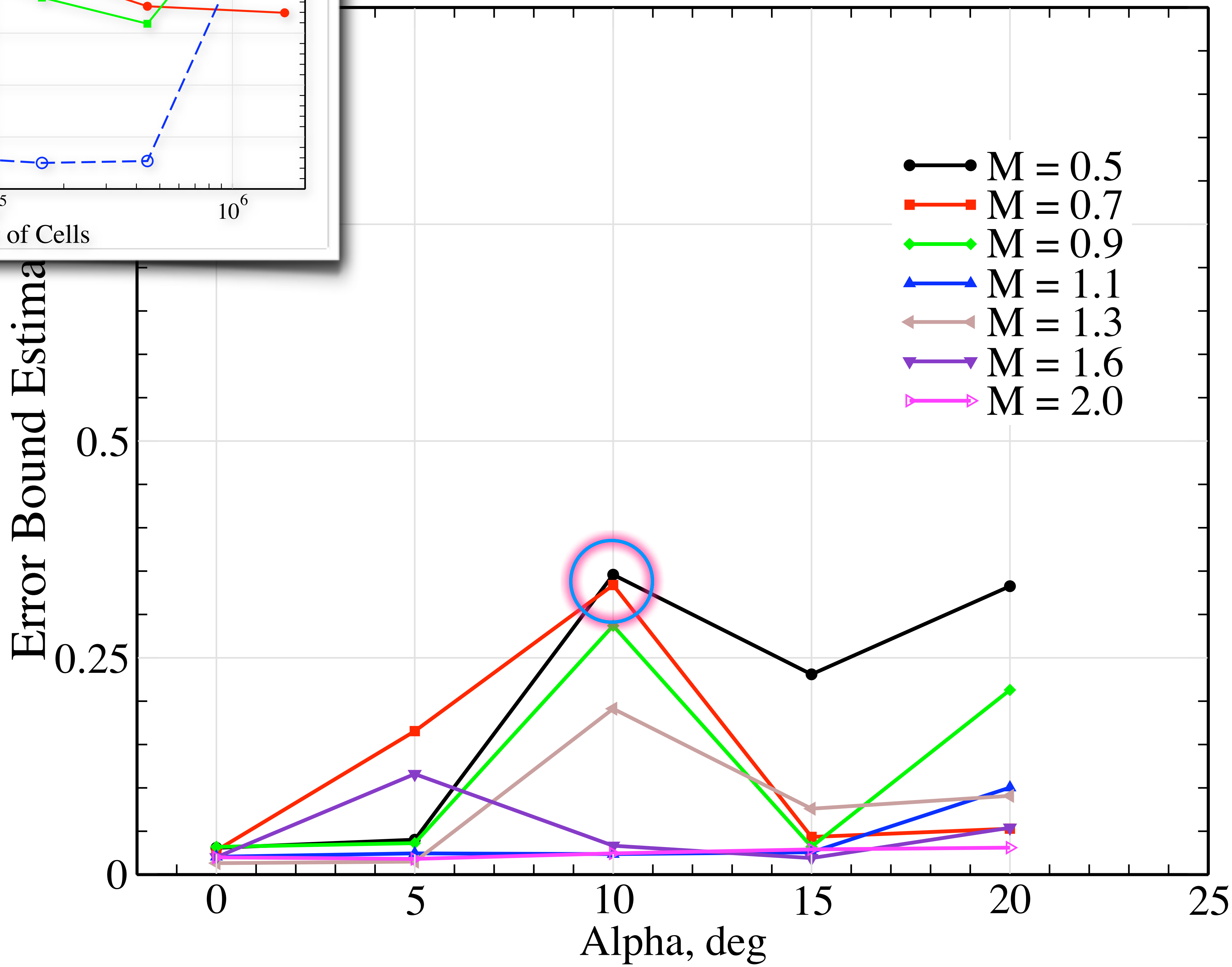
Error Controlled Aero Database

Error bound on output functional

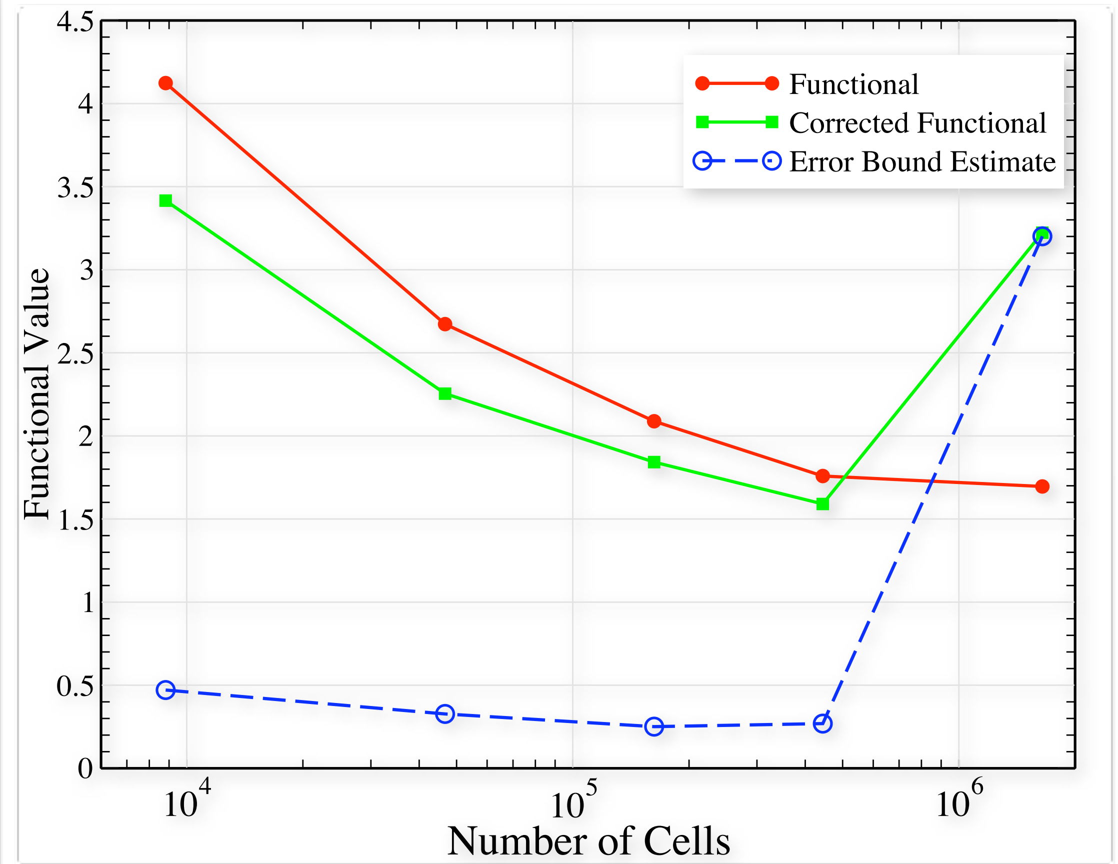


Database

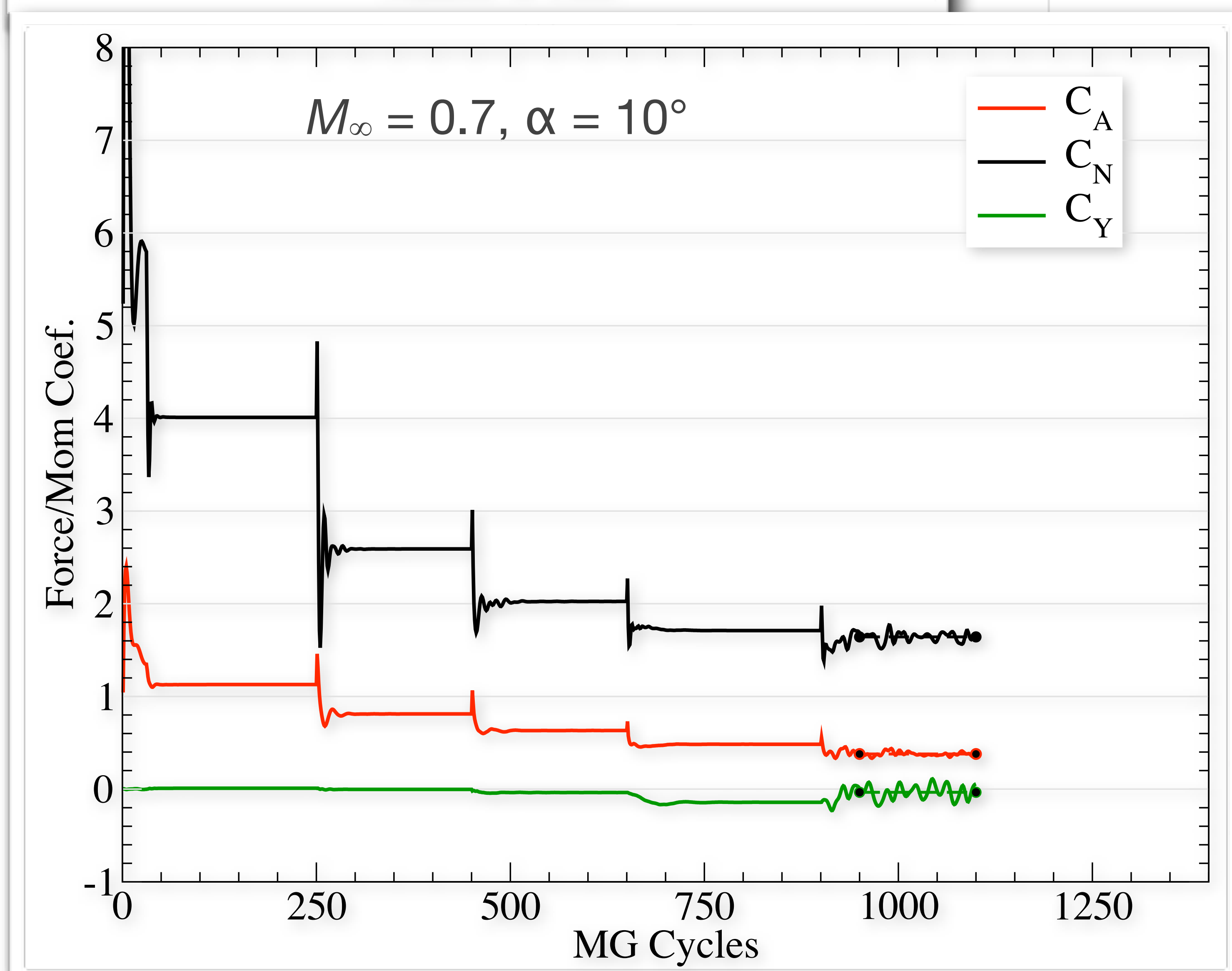

Functional
Corrected Functional
Error Bound Estimate
Functional Value
Number of Cells
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
10^4
10^5
10^6


M = 0.5
M = 0.7
M = 0.9
M = 1.1
M = 1.3
M = 1.6
M = 2.0
Error Bound Estima
0
0.25
0.5
0
5
10
15
20
25
Alpha, deg

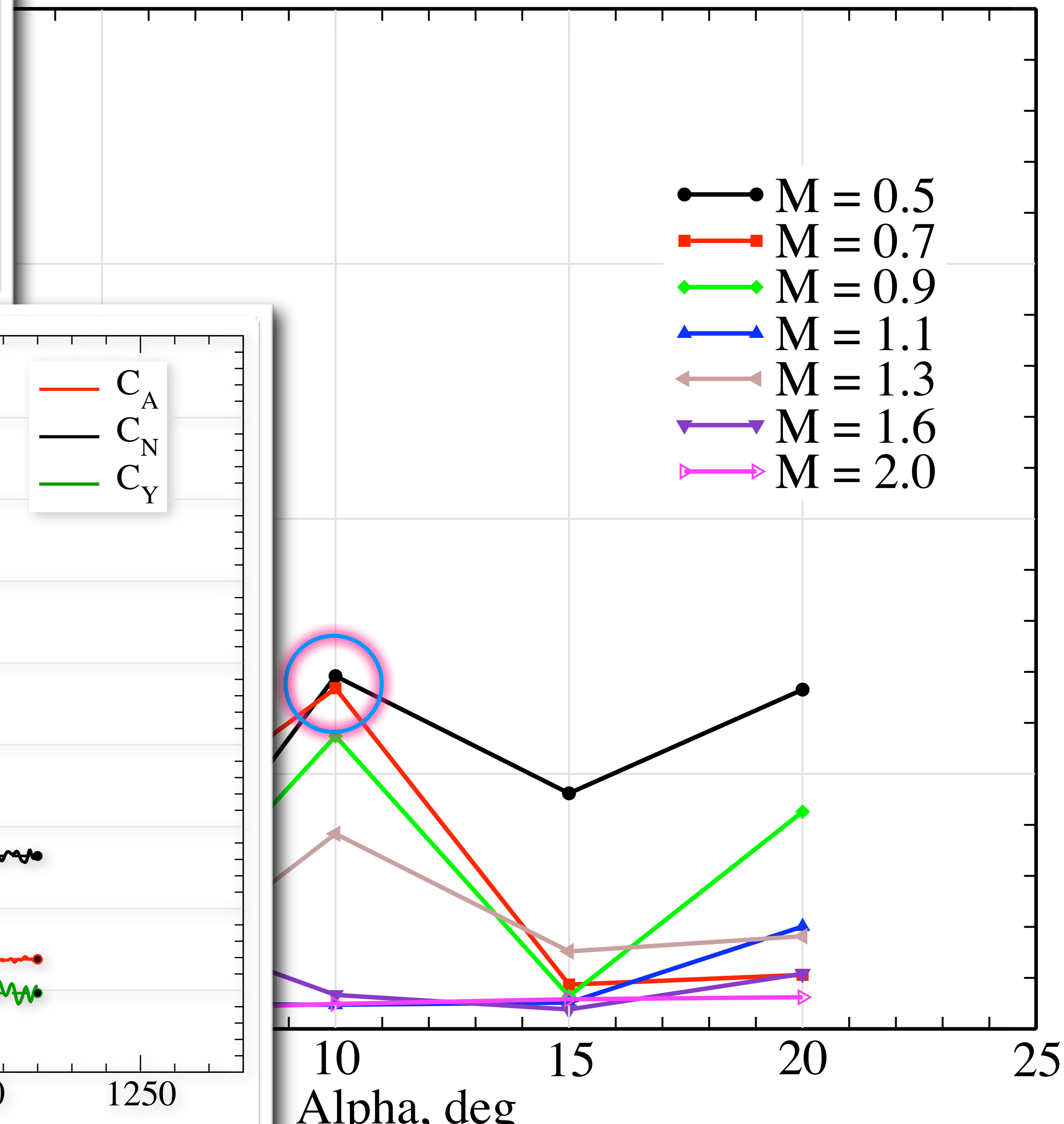
Database



Functional
Corrected Functional
Error Bound Estimate
Functional Value
Number of Cells

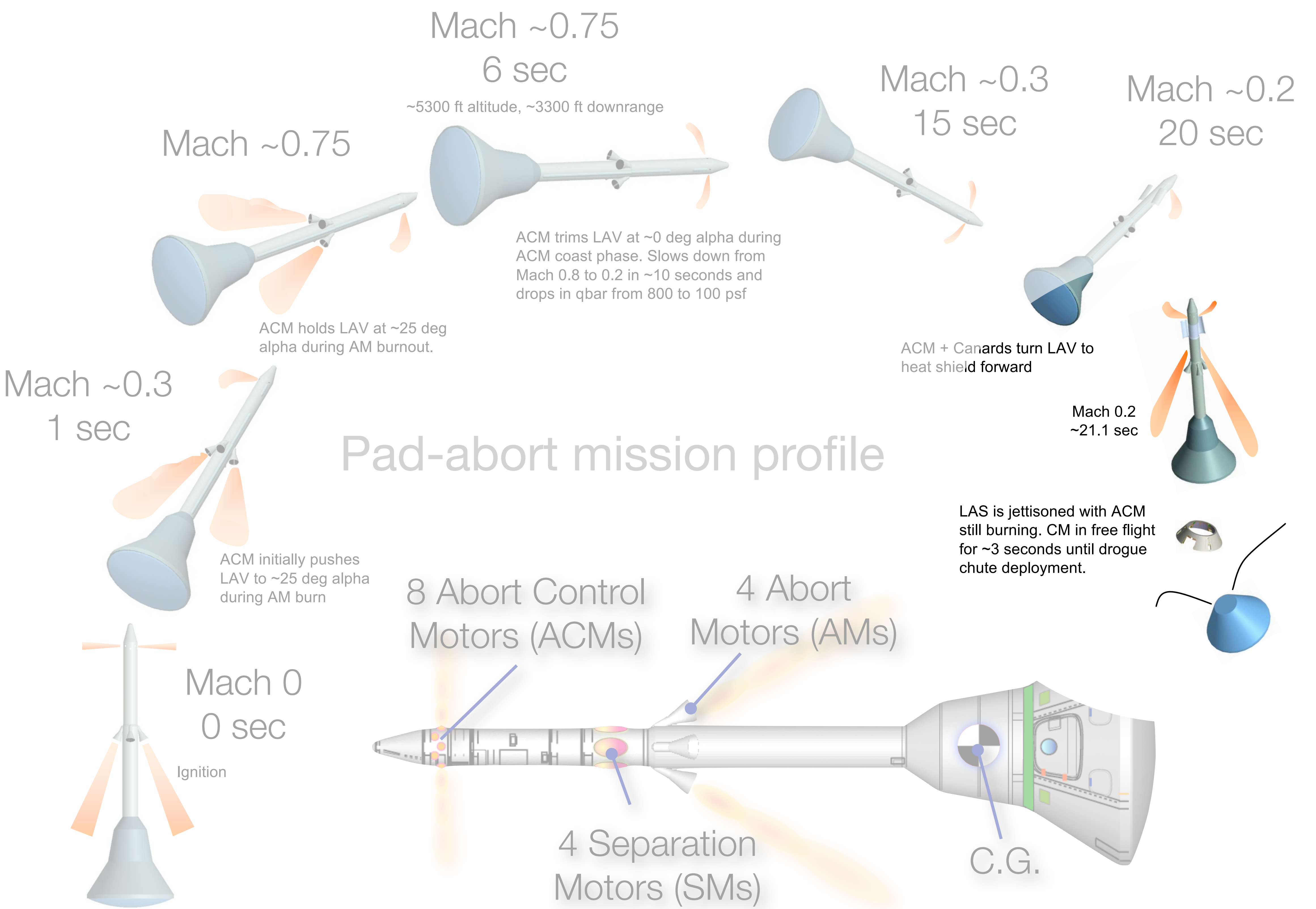


M_∞ = 0.7, α = 10°
C_A
C_N
C_Y
Force/Mom Coef.
MG Cycles



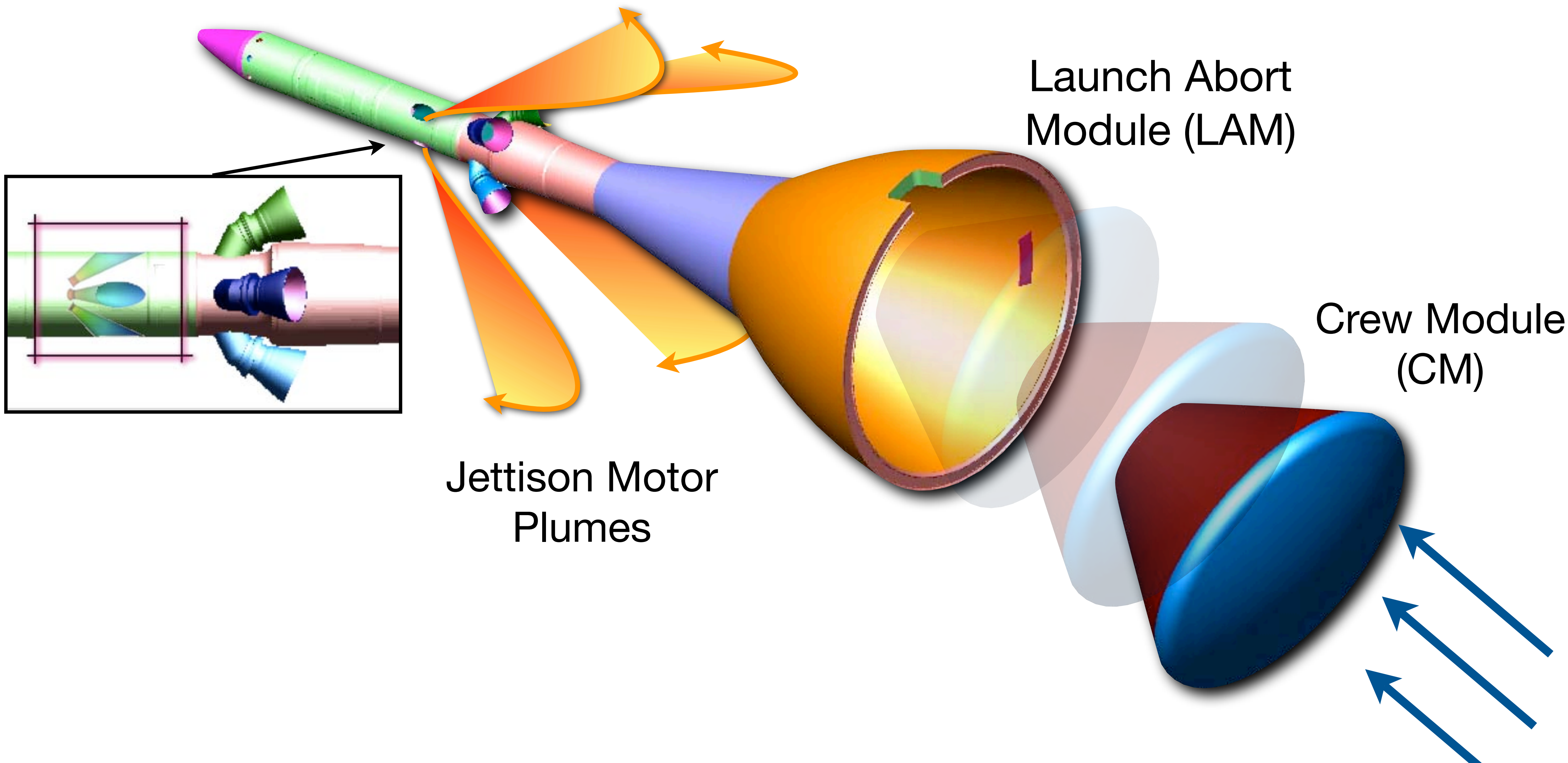
M = 0.5
M = 0.7
M = 0.9
M = 1.1
M = 1.3
M = 1.6
M = 2.0
Alpha, deg

Launch Abort System
Tower Jettison Database



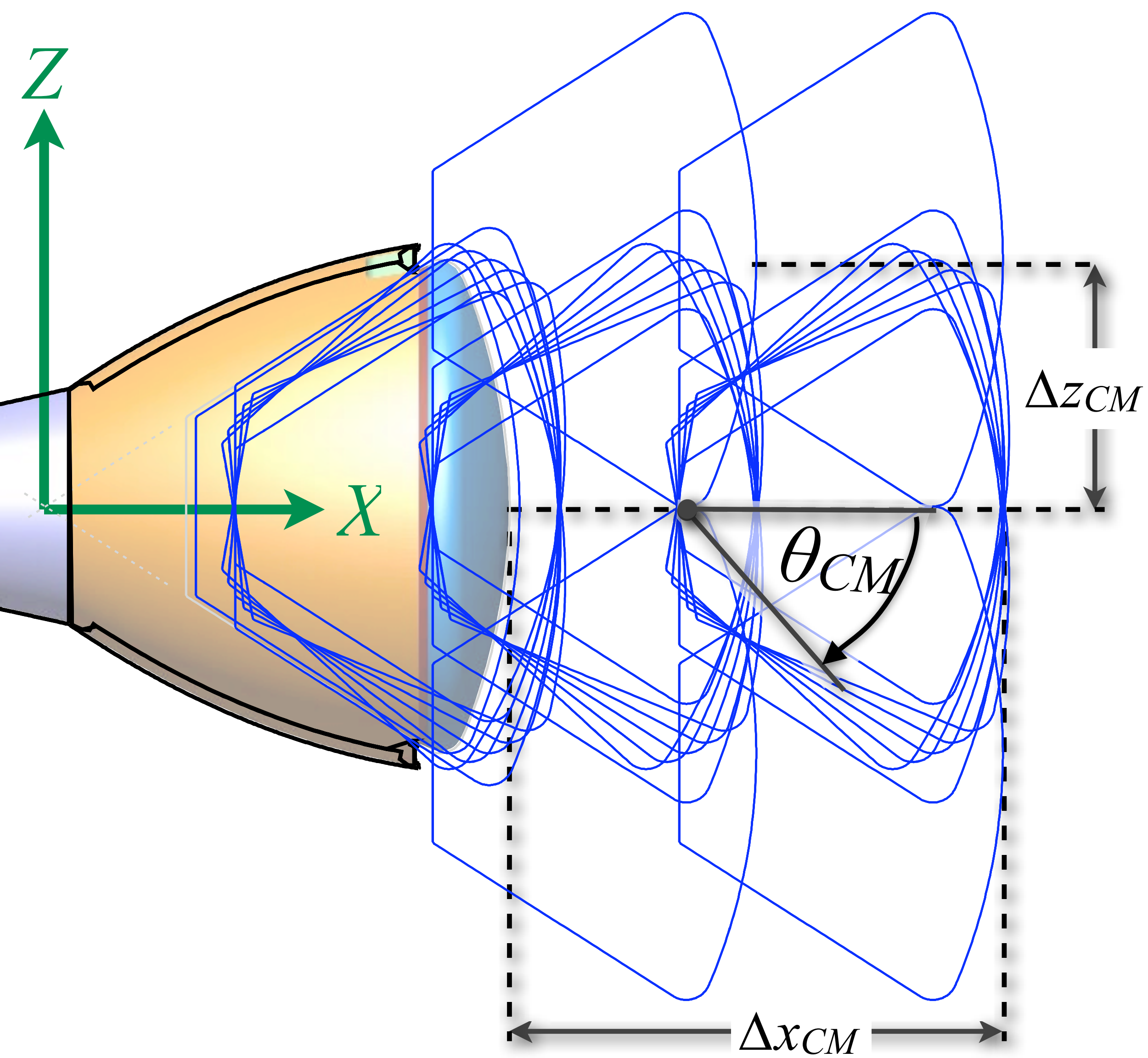
Launch Abort System Tower Jettison

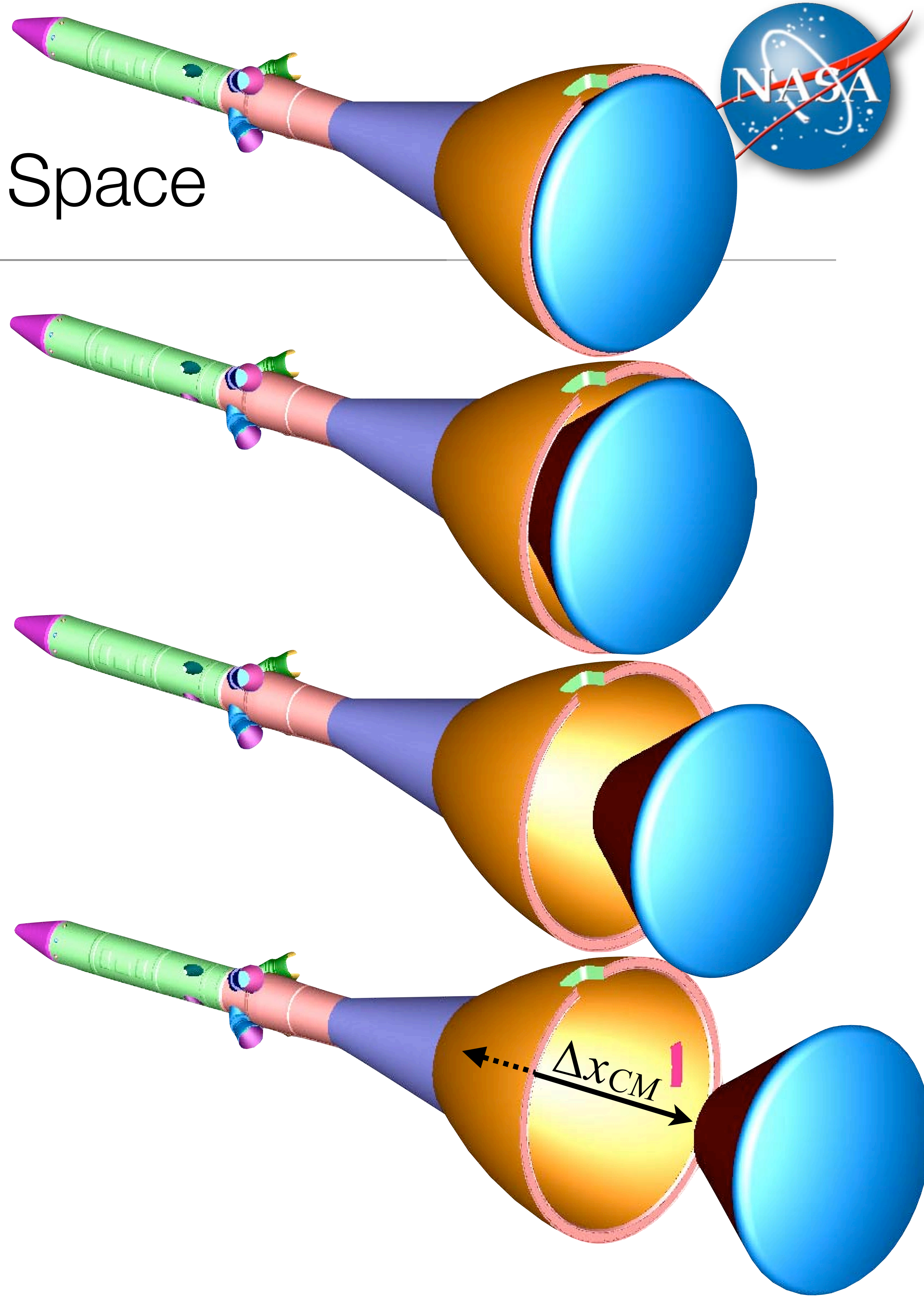
- Objective: Analyze aerodynamic forces and moments during LAS tower jettison
- Include effects of jettison motor firing with translation and rotation of the Crew Module (CM) relative to the Launch Abort Module



Geometry Configuration Space

- Four configuration parameters for CM position and orientation: Δx, Δy, Δz, θ





Database Cases

- Jettison Motor Plume Conditions:
  - JM on and JM off
  - Scale thrust for altitude
- Trajectory: maintain $q_\infty \approx$ Const.

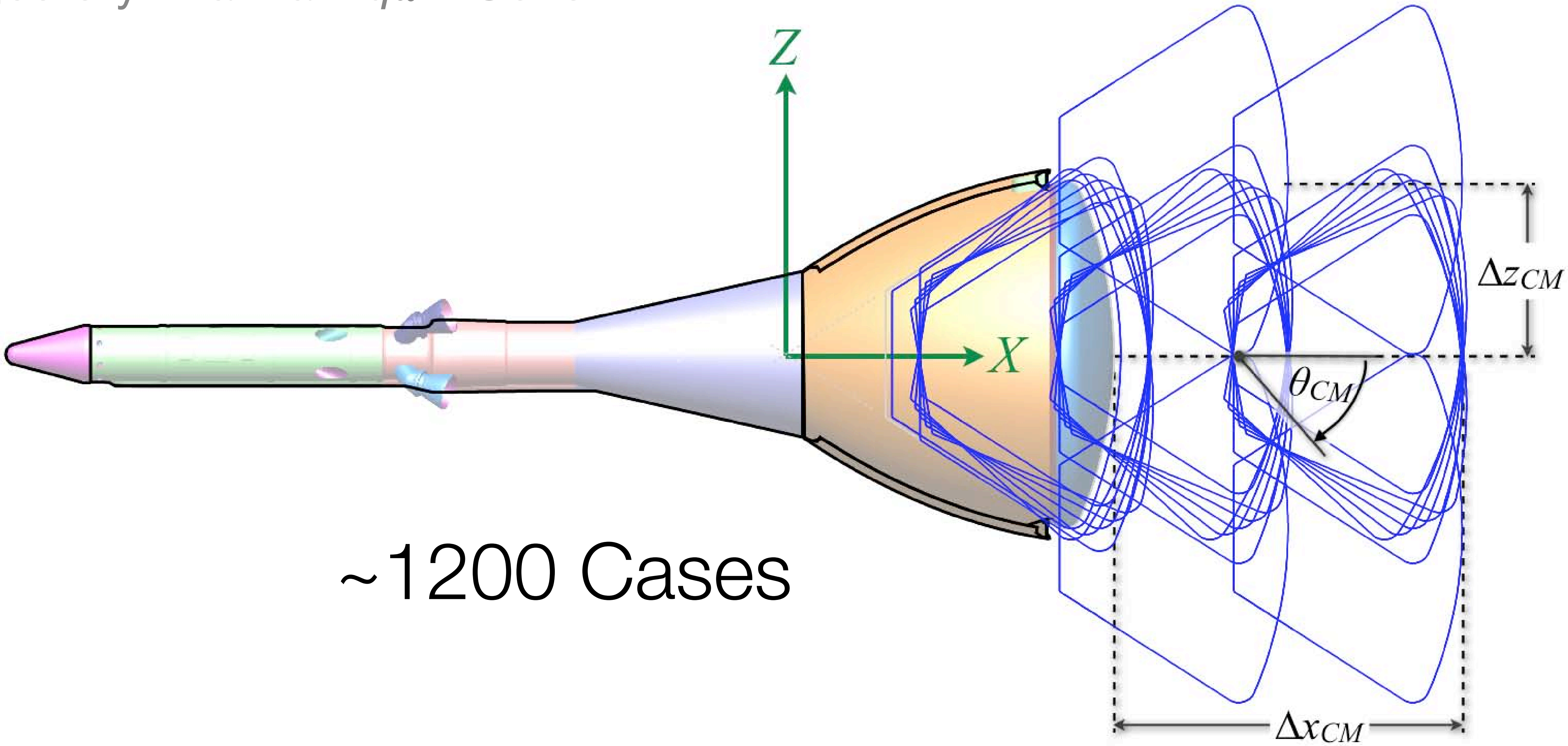
- Run Conditions:

  M_∞ = {0.5, 0.7, 0.9, 1.1, 1.3, 1.6}

  α = {155°, 160°, 165°, 170°, 175°, 180°}

  β = {0°, 5°}

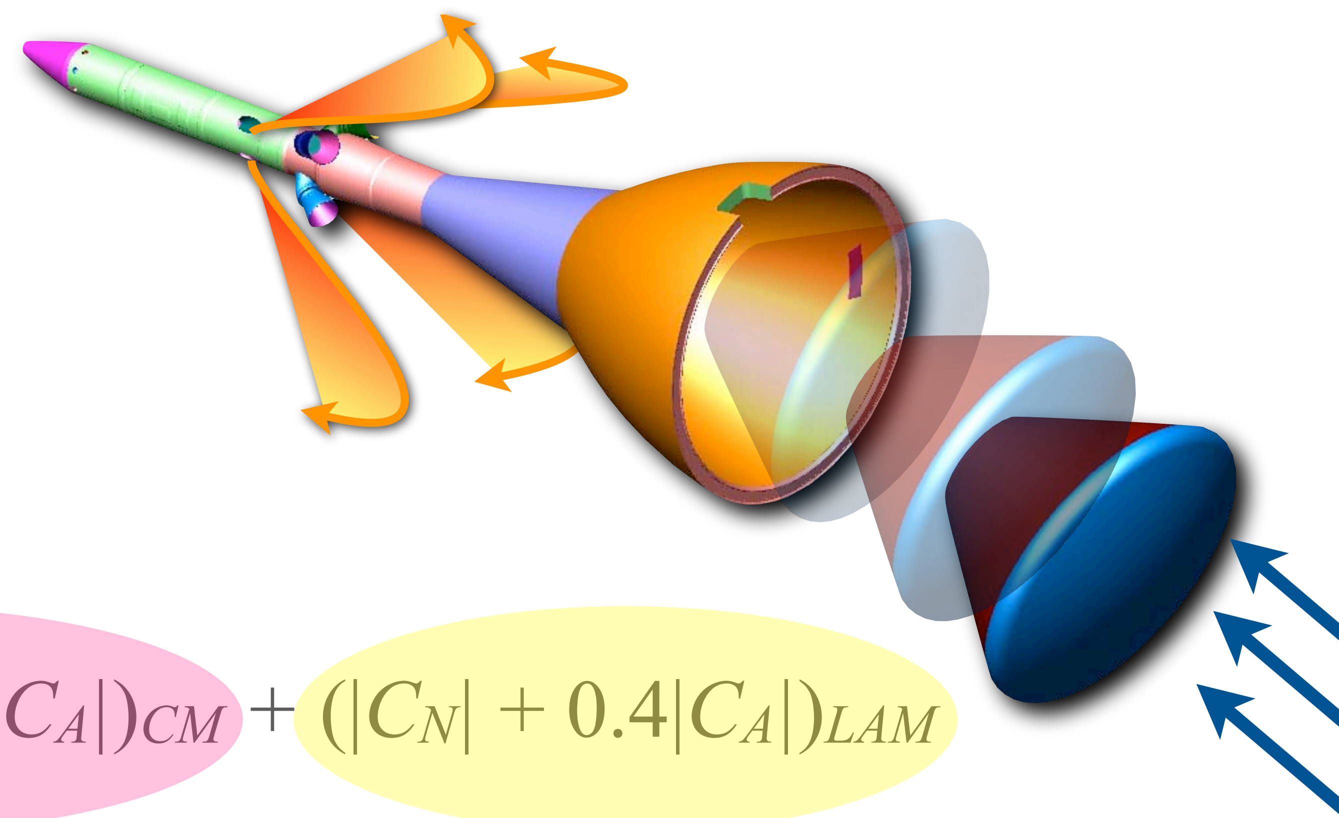
  CMΔx, CMΔy, CMΔz, CM$\Delta\theta$



~1200 Cases

Functional and Adaptation Strategy

- Challenging simulations
  - Complex, detailed geometry
  - Bodies in close proximity
  - Strong *upstream-firing* jets
  - Shocks and wakes



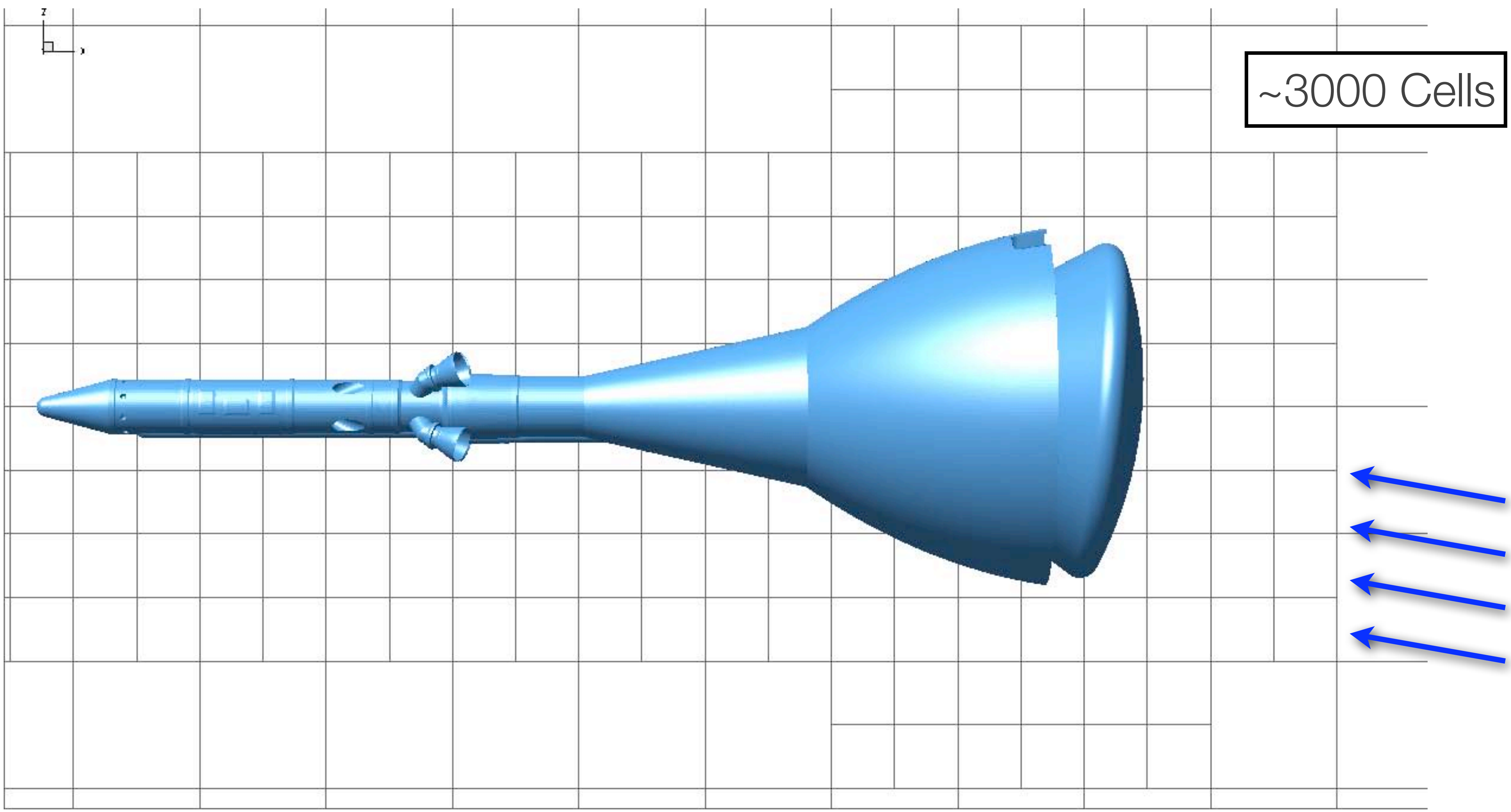
- Output functional: $J = (0.8|C_N| + 0.2|C_A|)_{CM} + (|C_N| + 0.4|C_A|)_{LAM}$

Capture forces on CM *Capture forces on tower*

- Solution technique is a compromise since most of these cases are unsteady, and need high resolution
  - Want the best answer as cheaply as possible
- Adaptation follows "worst-things-first" strategy (*AIAA 2008-0725*)
  - Refine largest contributors to output error first

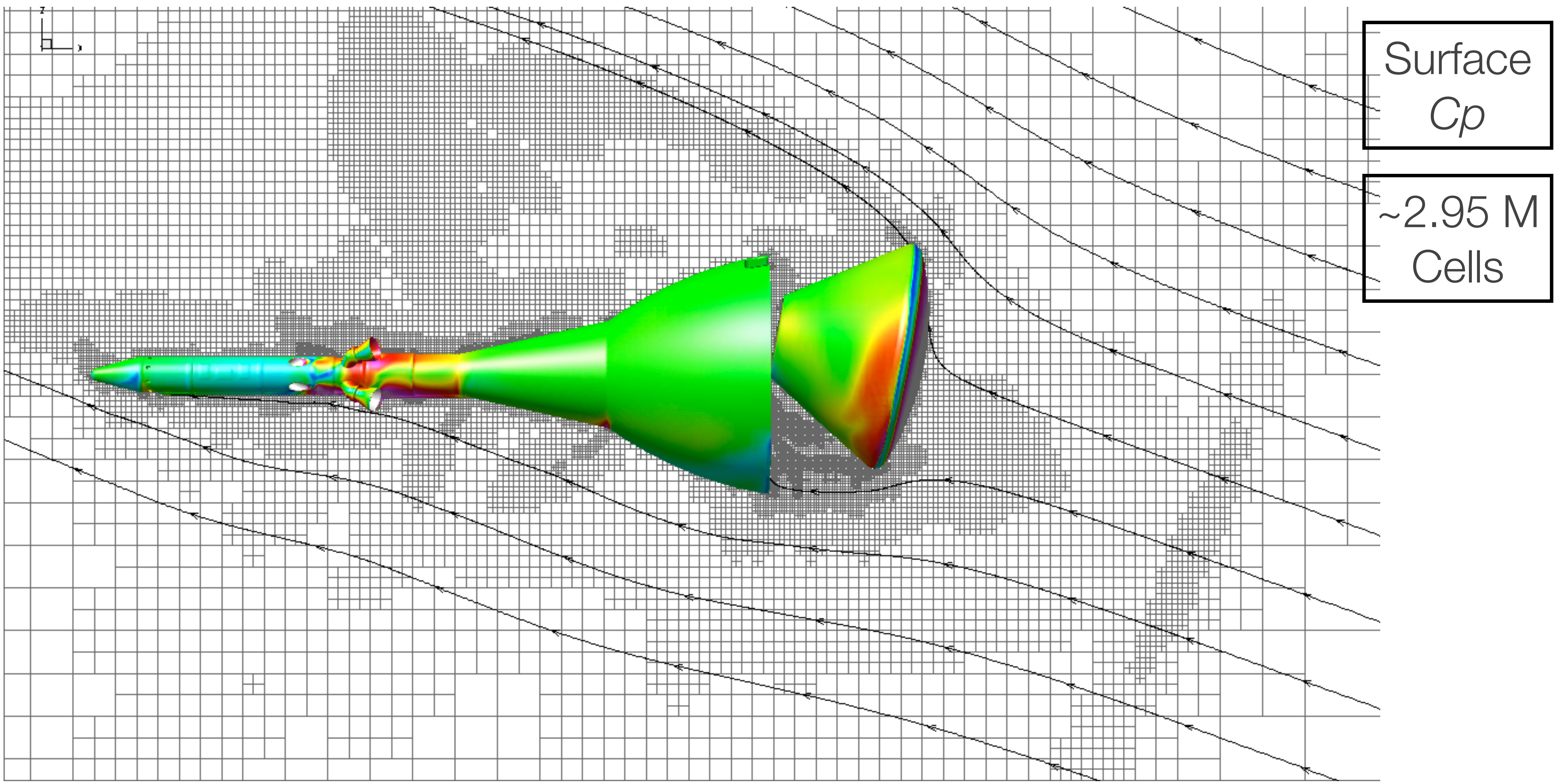
Initial Mesh

- Background mesh essentially symmetric and coarse to avoid biasing solution



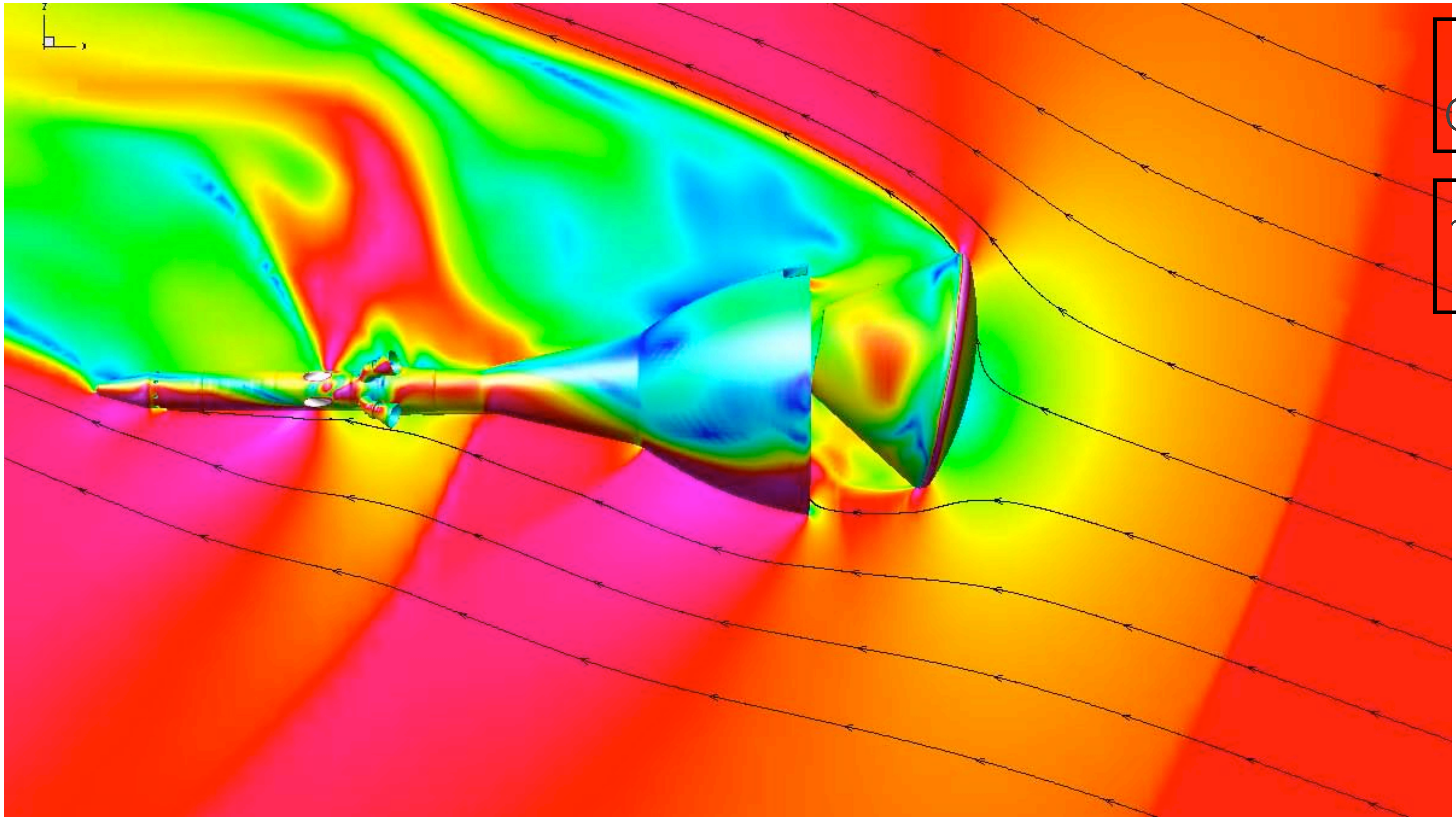
Example Final Mesh (10 Adapt Cycles)

- Output functional: $J = (0.8|C_N| + 0.2|C_A|)_{CM} + (|C_N| + 0.4|C_A|)_{LAM}$
- $M_\infty = 1.1$, $\alpha = 160°$ with the CM @ (Δx, Δy, Δz, 10°)



Example Final Solution (10 Adapt Cycles)

- Output functional: $J = (0.8|C_N| + 0.2|C_A|)_{CM} + (|C_N| + 0.4|C_A|)_{LAM}$
- $M_\infty = 1.1$, $\alpha = 160°$ with the CM @ (Δx, Δy, Δz, 10°)

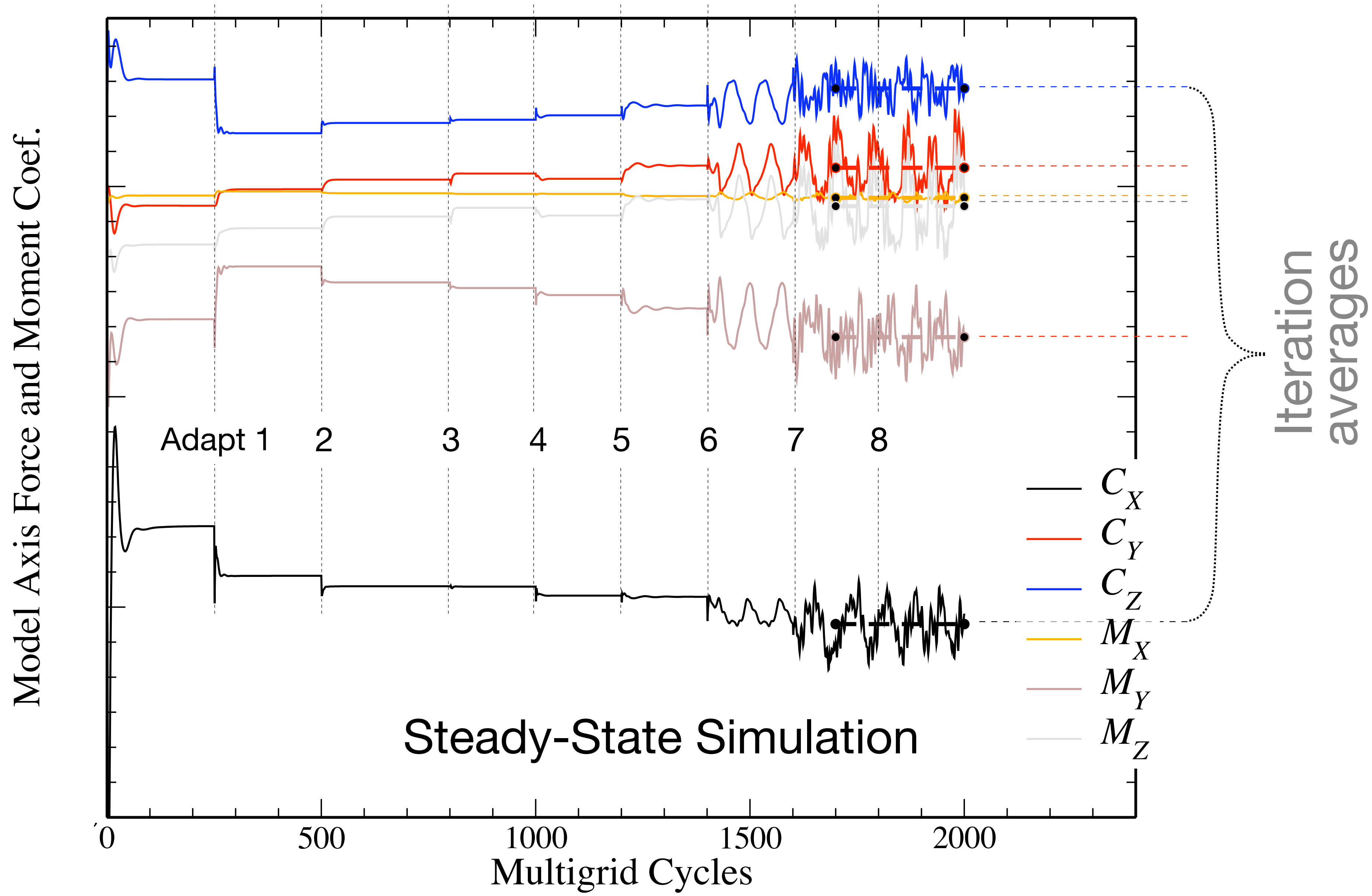


Mach Contours

~2.95 M Cells

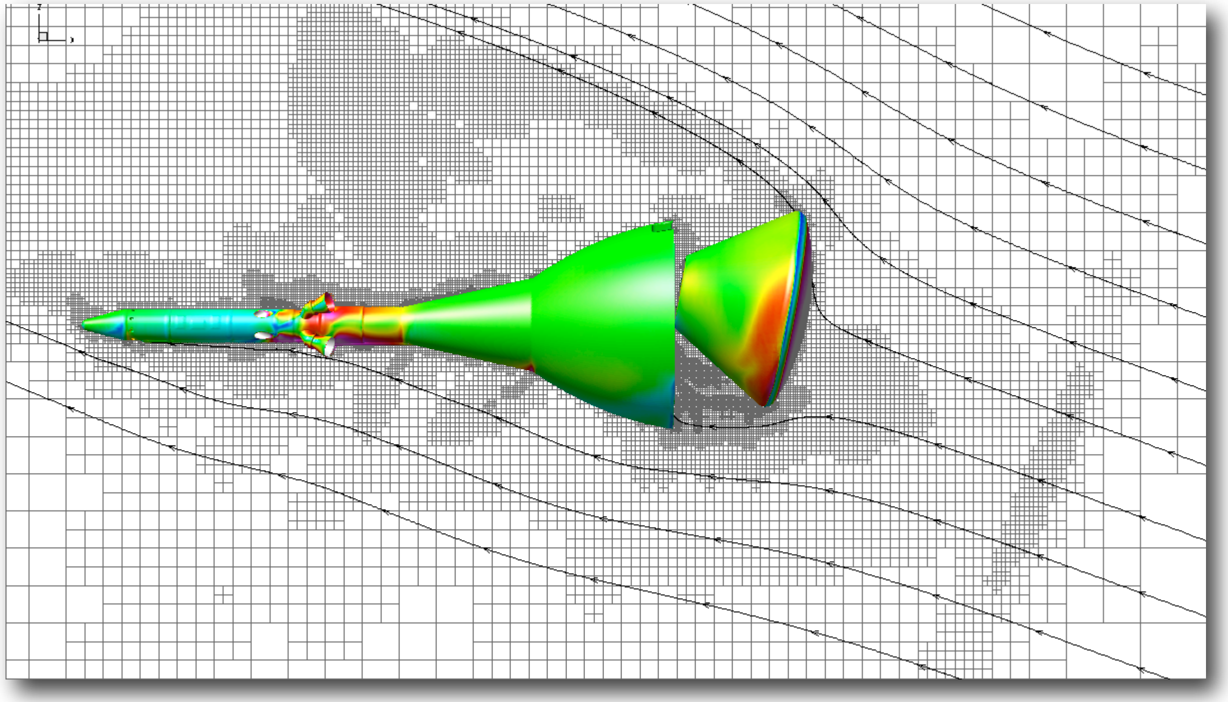
Convergence of Aerodynamic Coefficients

- Output functional: $J = (0.8|C_N| + 0.2|C_A|)_{CM} + (|C_N| + 0.4|C_A|)_{LAM}$
- $M_\infty = 1.1$, $\alpha = 160°$ with the CM @ (Δx, Δy, Δz, 10°)
- Convergence of forces and moms. on CM with mesh refinement

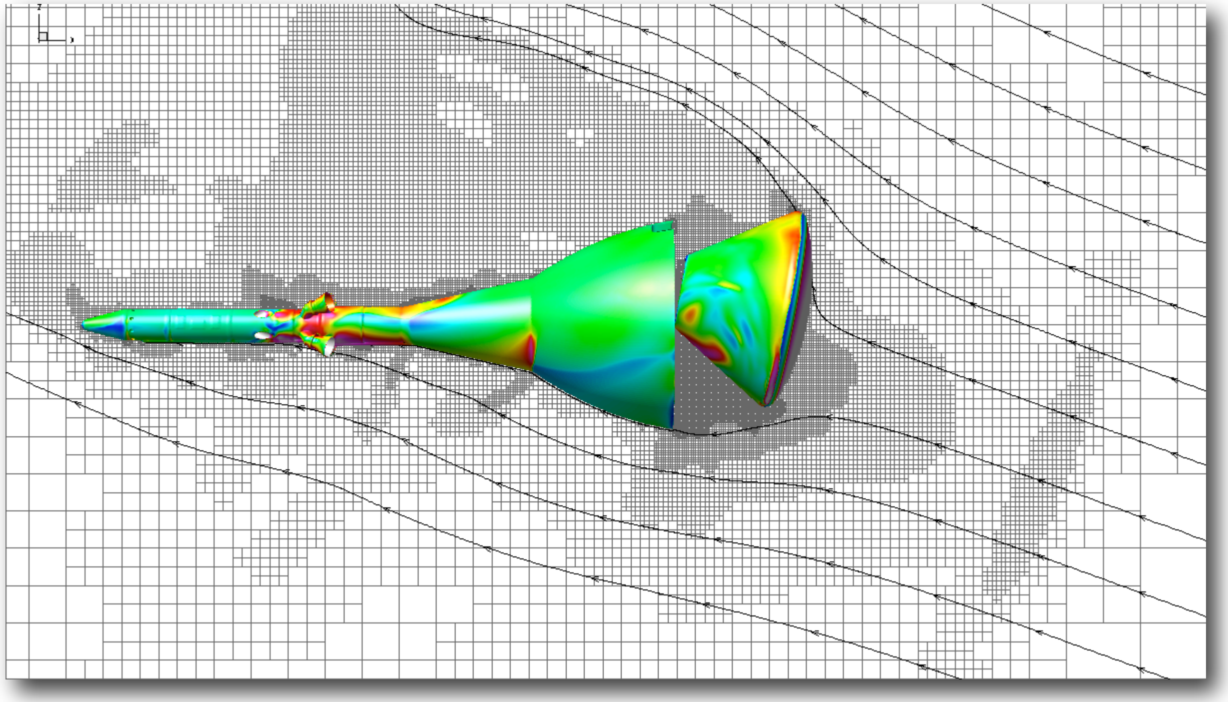


Comparison with Unsteady Simulation

- How do these iteration averages compare with unsteady simulation?
- Performed comparisons at Mach 0.7, & 1.1
- “Best unsteady mesh” generated by 1 additional refinement of steady mesh, using low threshold to “fill out” adaptation regions
- Example case: $M_\infty = 1.1$, $\alpha = 160°$ with the CM @ (Δx, Δy, Δz, 10°)



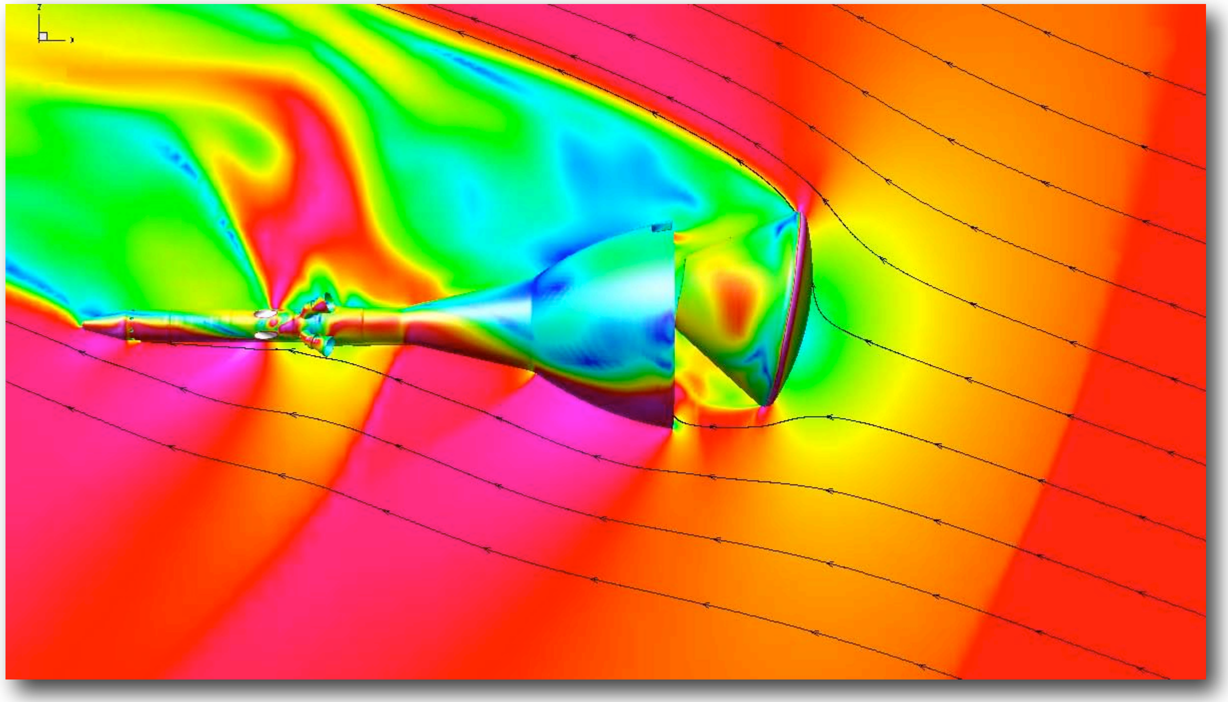
Steady mesh & *Cp,* ~2.95M Cells



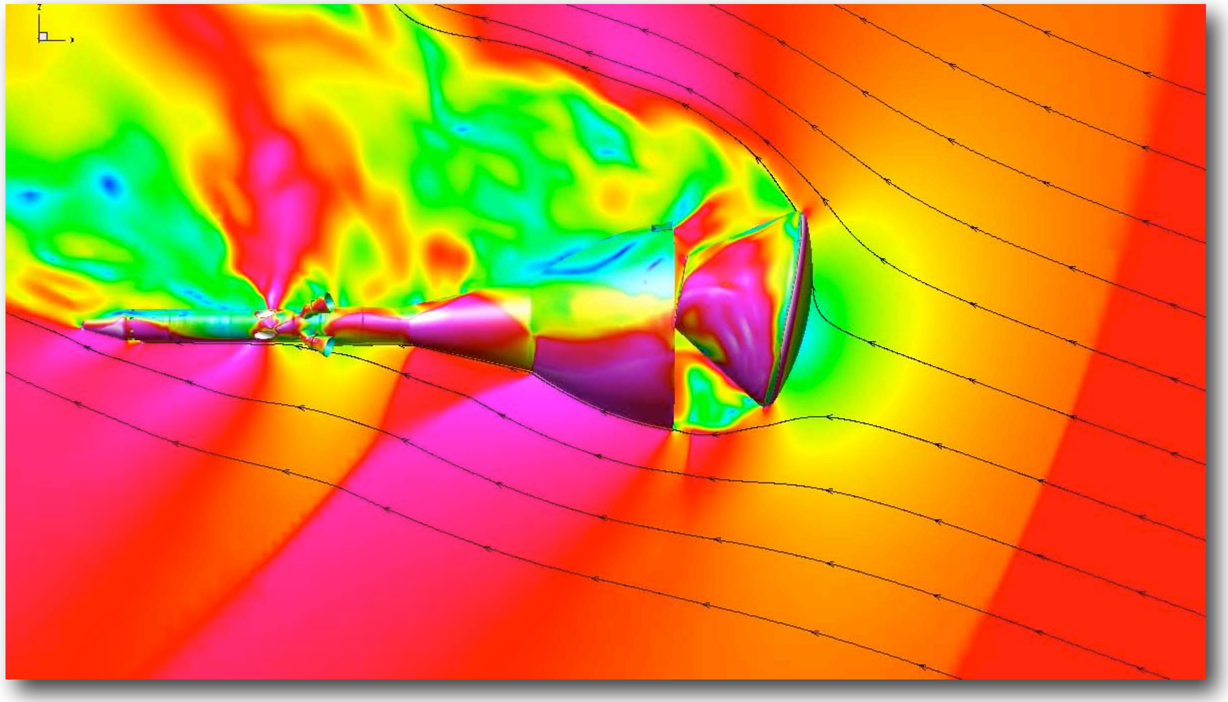
Unsteady mesh & *Cp,* ~5.2M Cells

Comparison with Unsteady Simulation

- How do these iteration averages compare with unsteady simulation?
- Performed comparisons at Mach 0.7, & 1.1
- “Best unsteady mesh” generated by 1 additional refinement of steady mesh, using low threshold to “fill out” adaptation regions
- Example case: $M_\infty = 1.1$, $\alpha = 160°$ with the CM @ (Δx, Δy, Δz, 10°)



Steady mesh iso-Mach, ~2.95M Cells

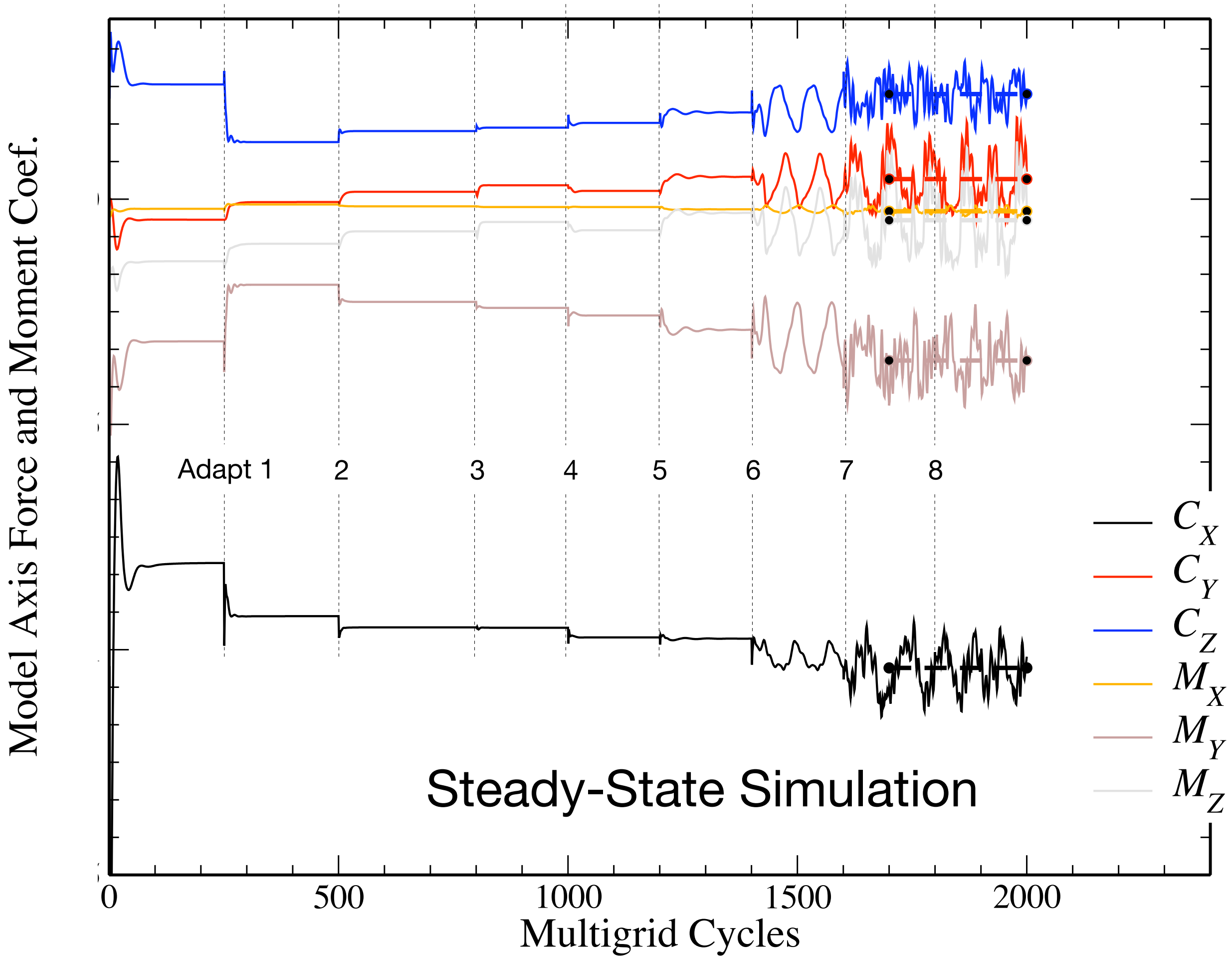


Unsteady mesh iso-Mach, ~5.2M Cells

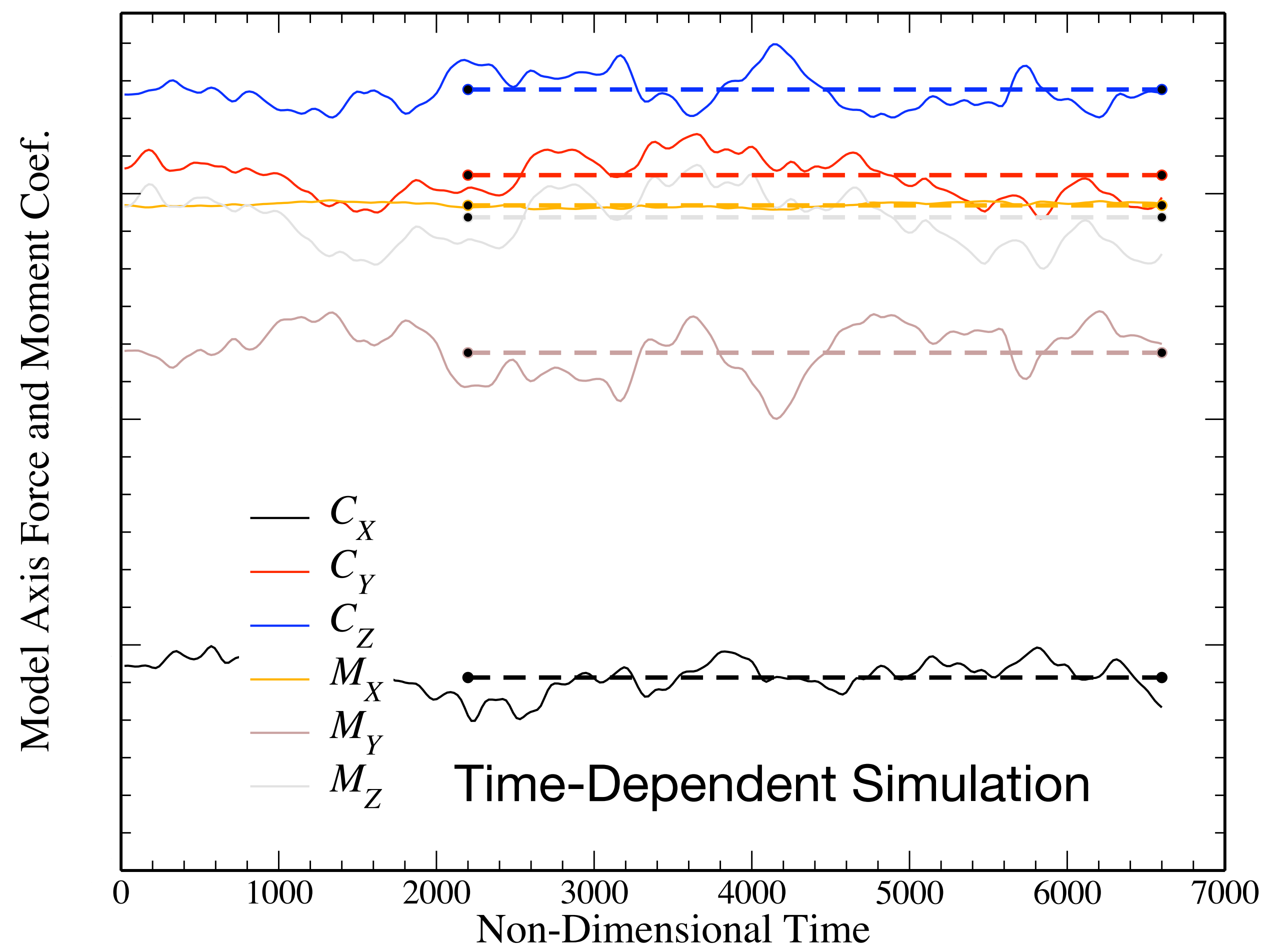
Comparison with Unsteady Simulation

$M_\infty = 1.1$, $\alpha = 160°$ with the CM @ (Δx, Δy, Δz, 10°)

Steady, ~2.95M Cells



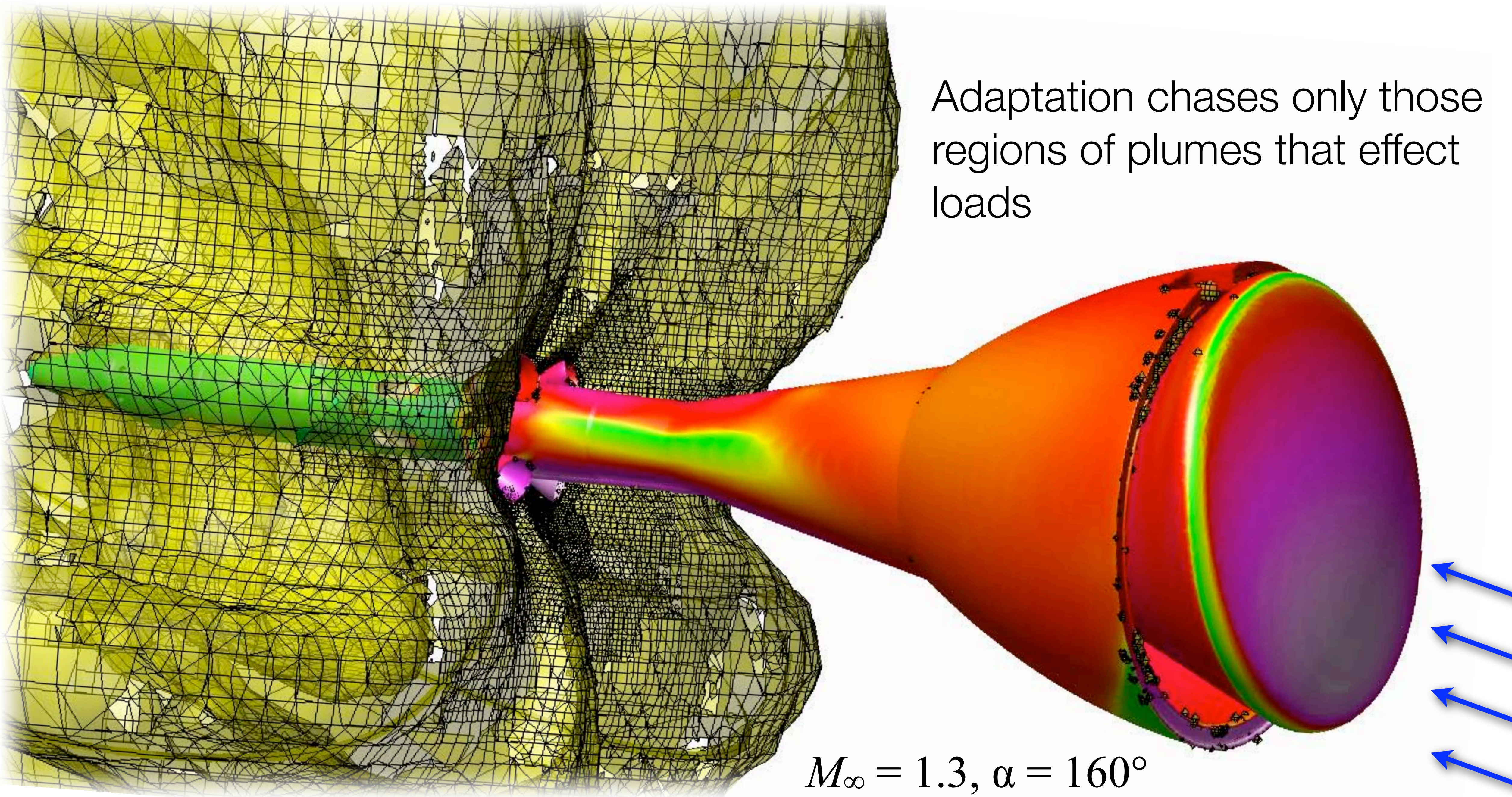
Unsteady, ~5.2M Cells



- Agreement to third significant digit
- Differences in averages are same size as differences due to averaging window
- Similar results for other components at both Mach 0.7 & Mach 1.1

Plume Shape

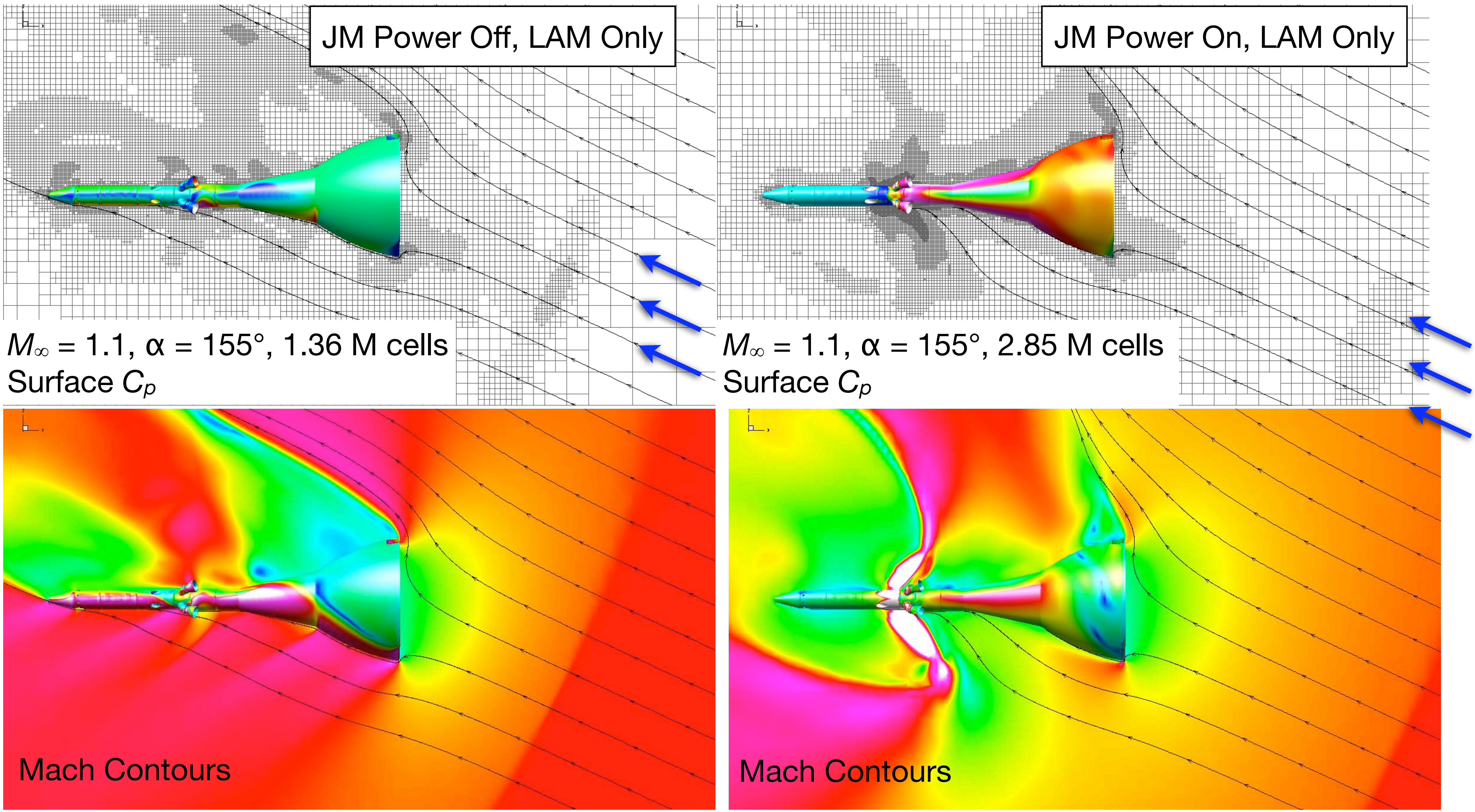
T_o iso-surface showing approximate plume shape



Adaptation chases only those regions of plumes that effect loads

$M_\infty = 1.3, \alpha = 160°$

Comparison of JM On and Off Flowfields

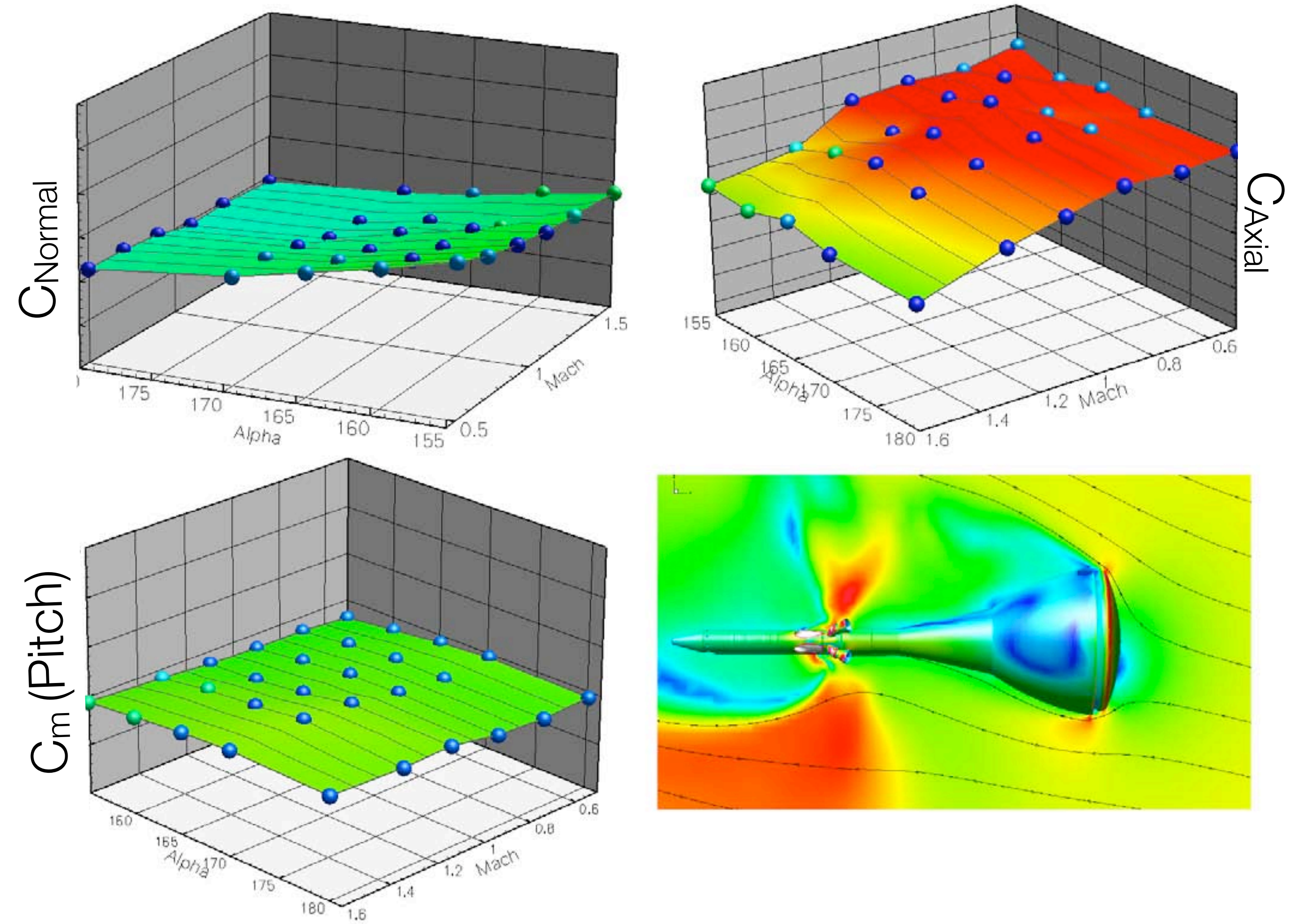


JM plumes move bow shock ~18 ft upstream

Database Samples

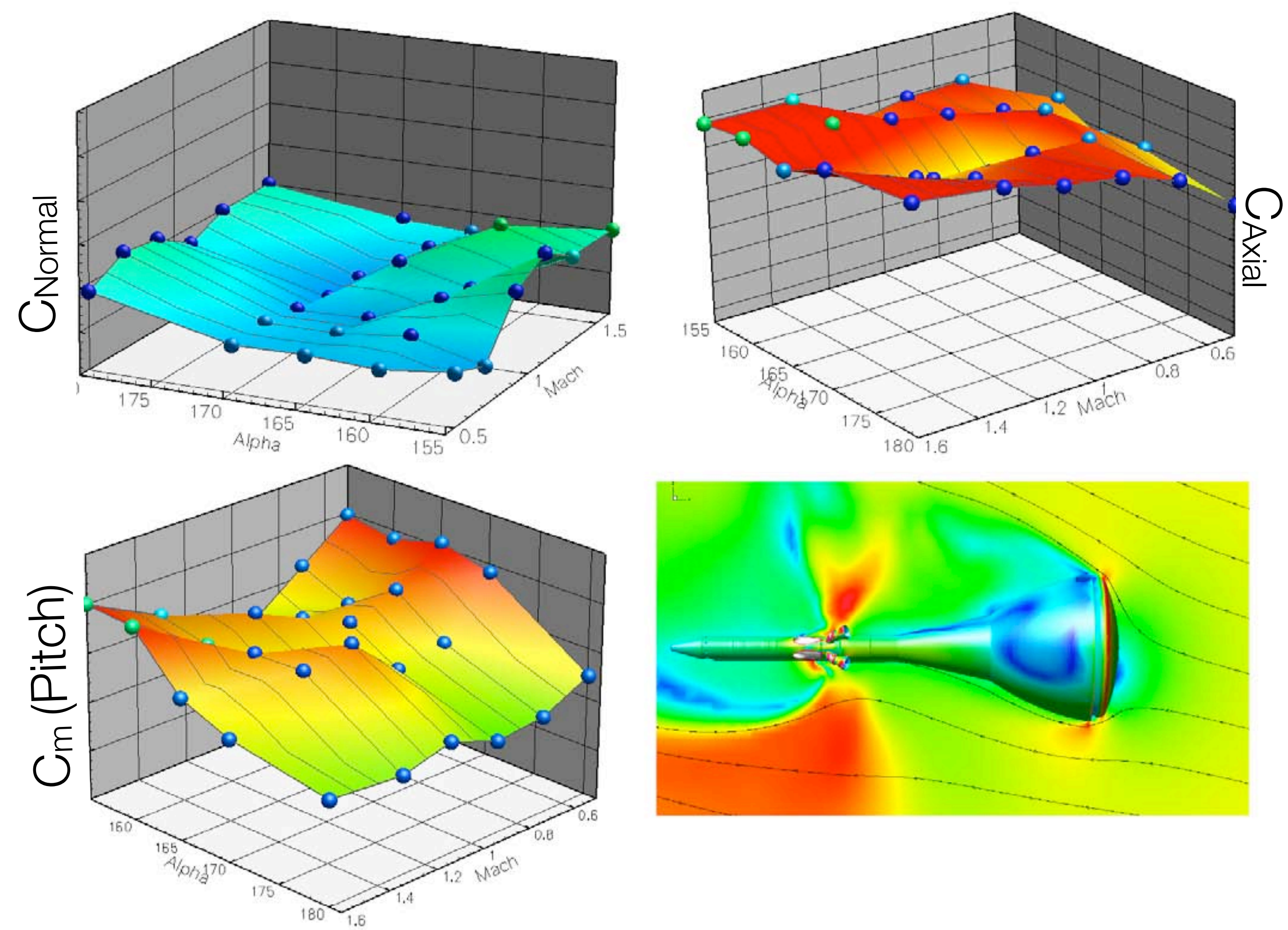
Loads on CM and LAM in proximity

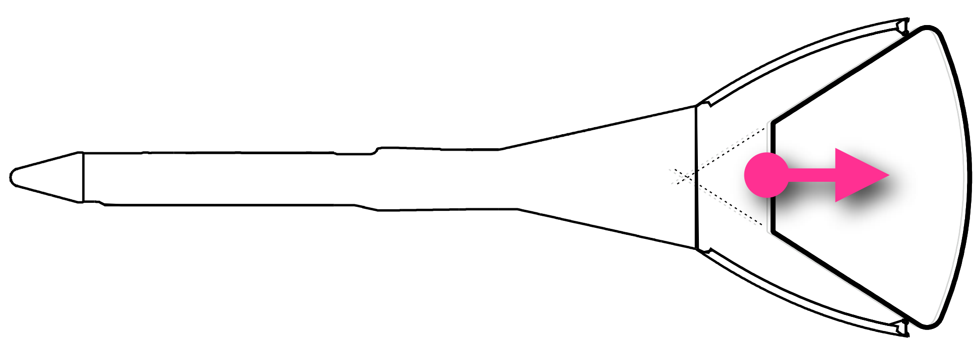
(Δx, 0.0, 0.0, 0°)



Loads on CM

Loads on LAM

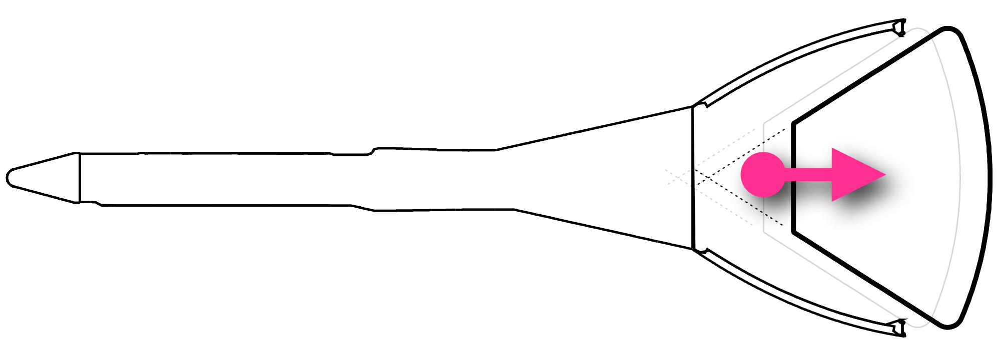




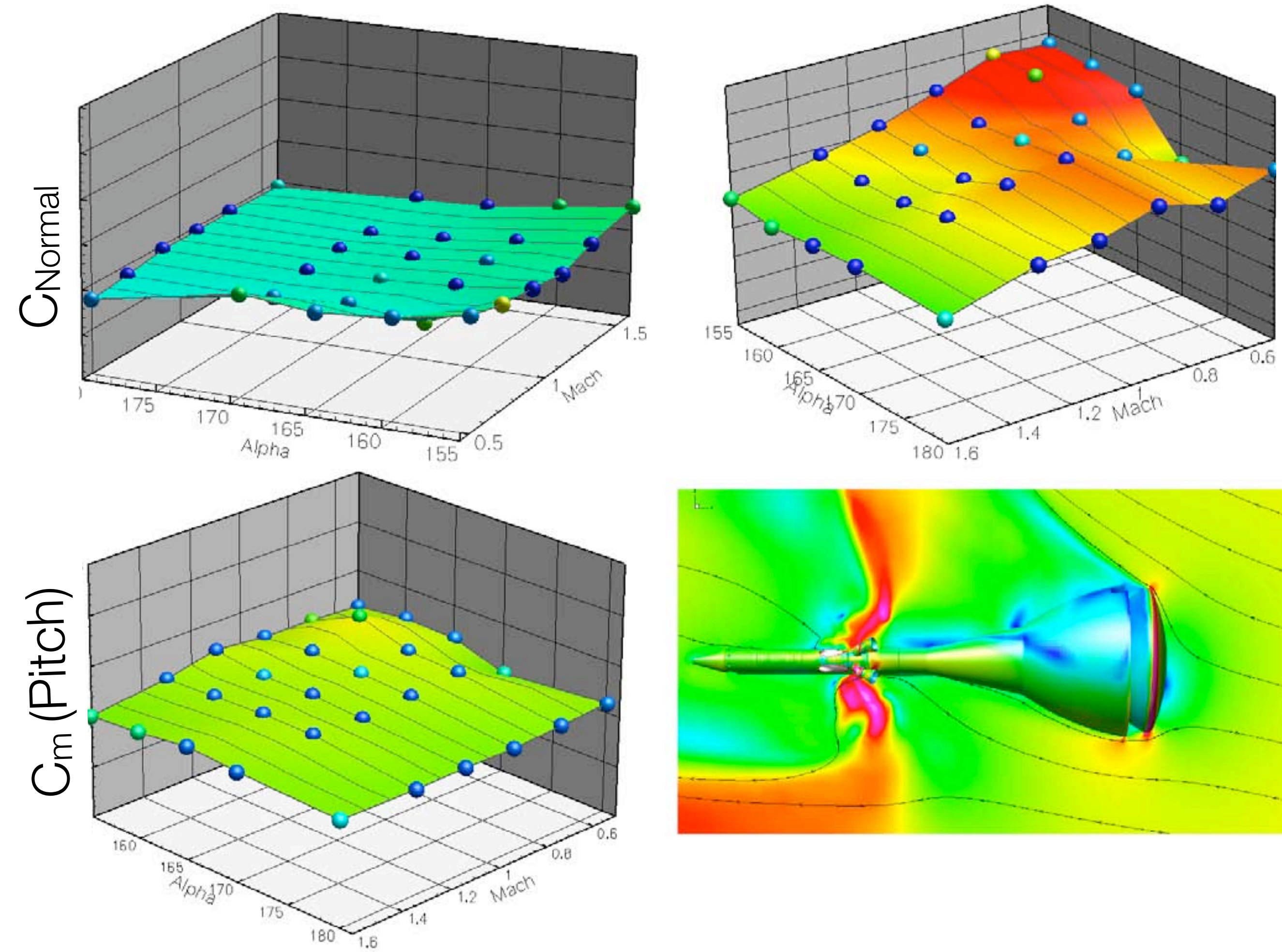
Database Samples

Loads on CM and LAM in proximity

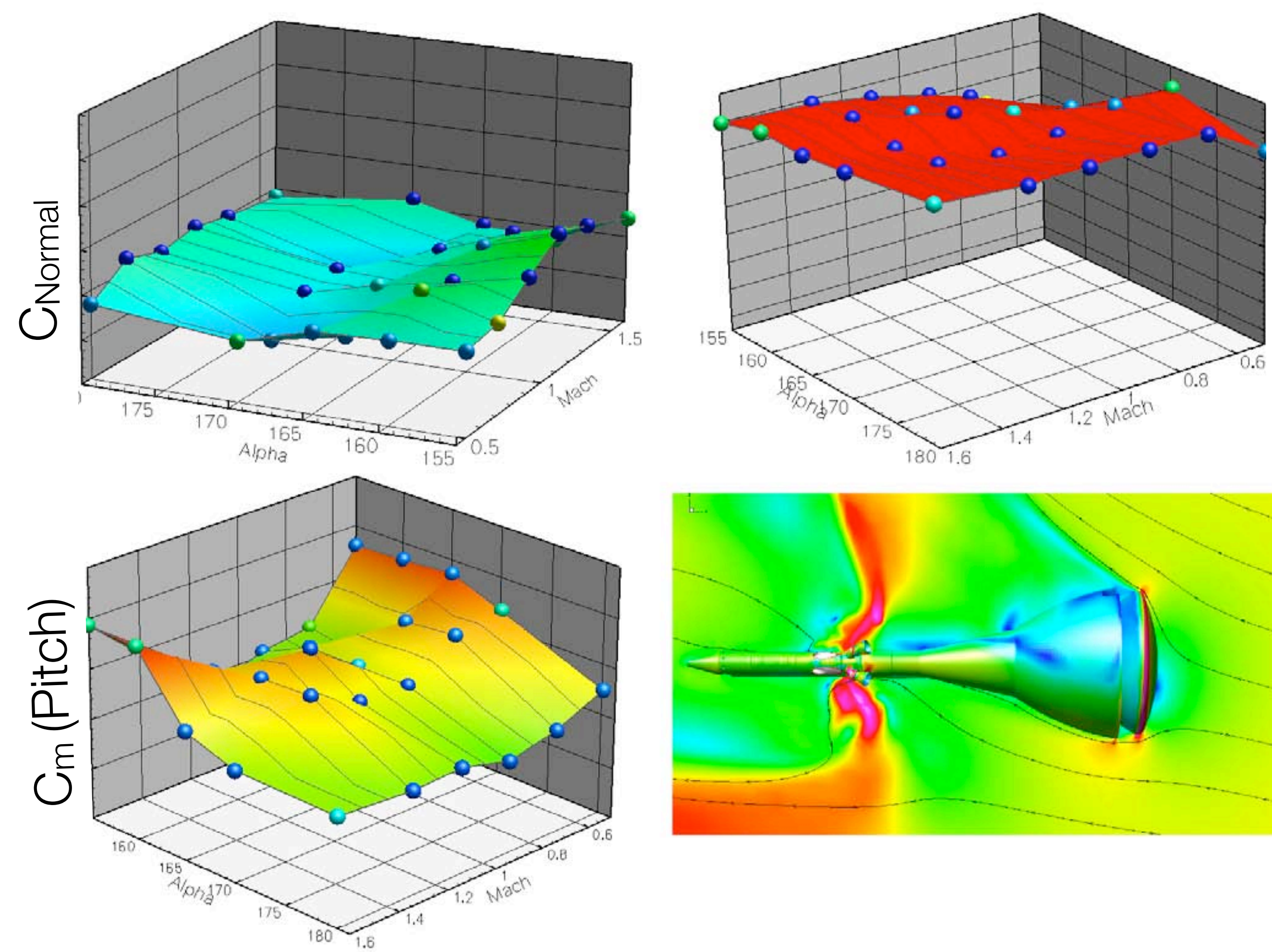
(Δx, 0.0, 0.0, 0°)



Loads on CM



Loads on LAM

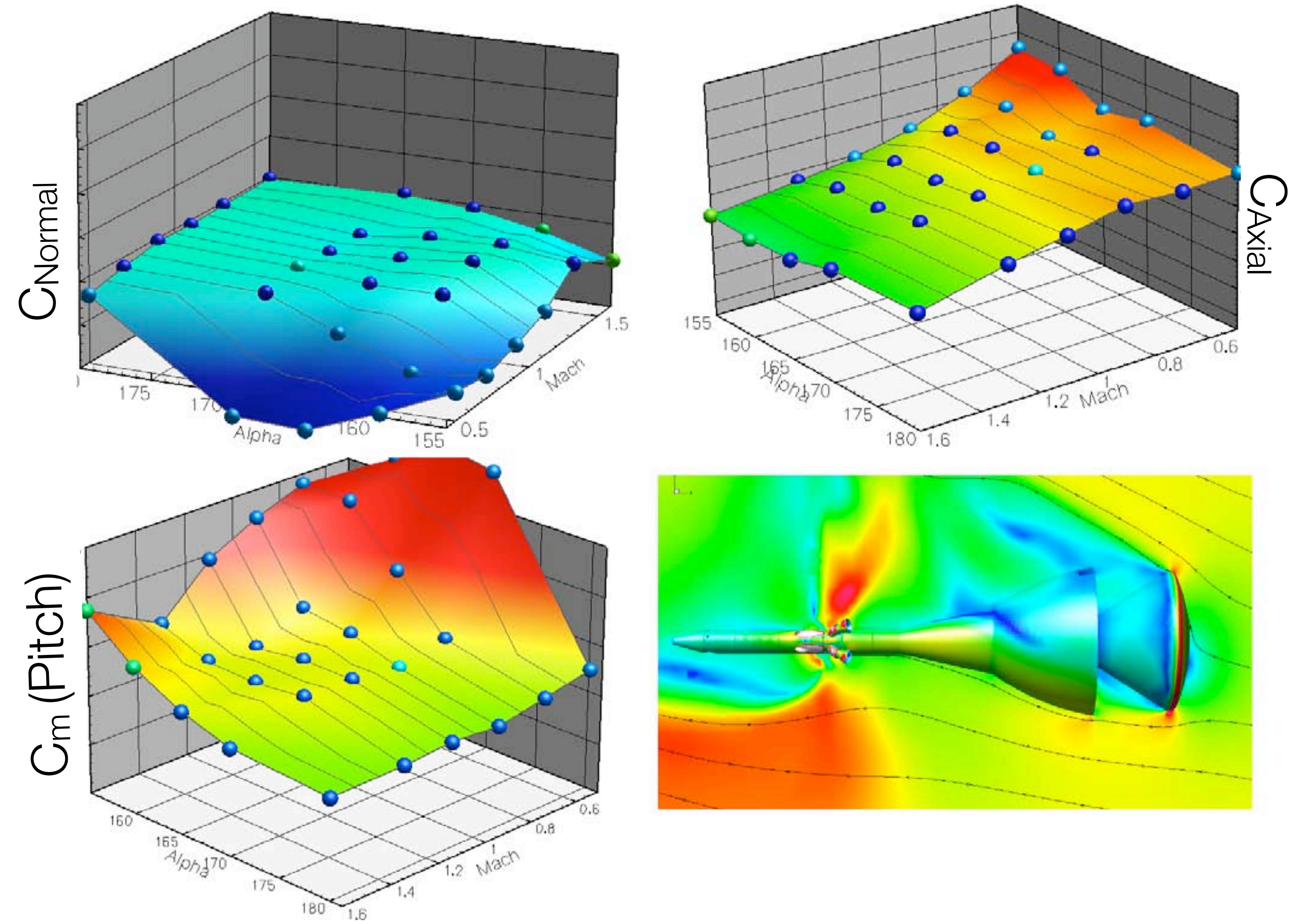


Database Samples

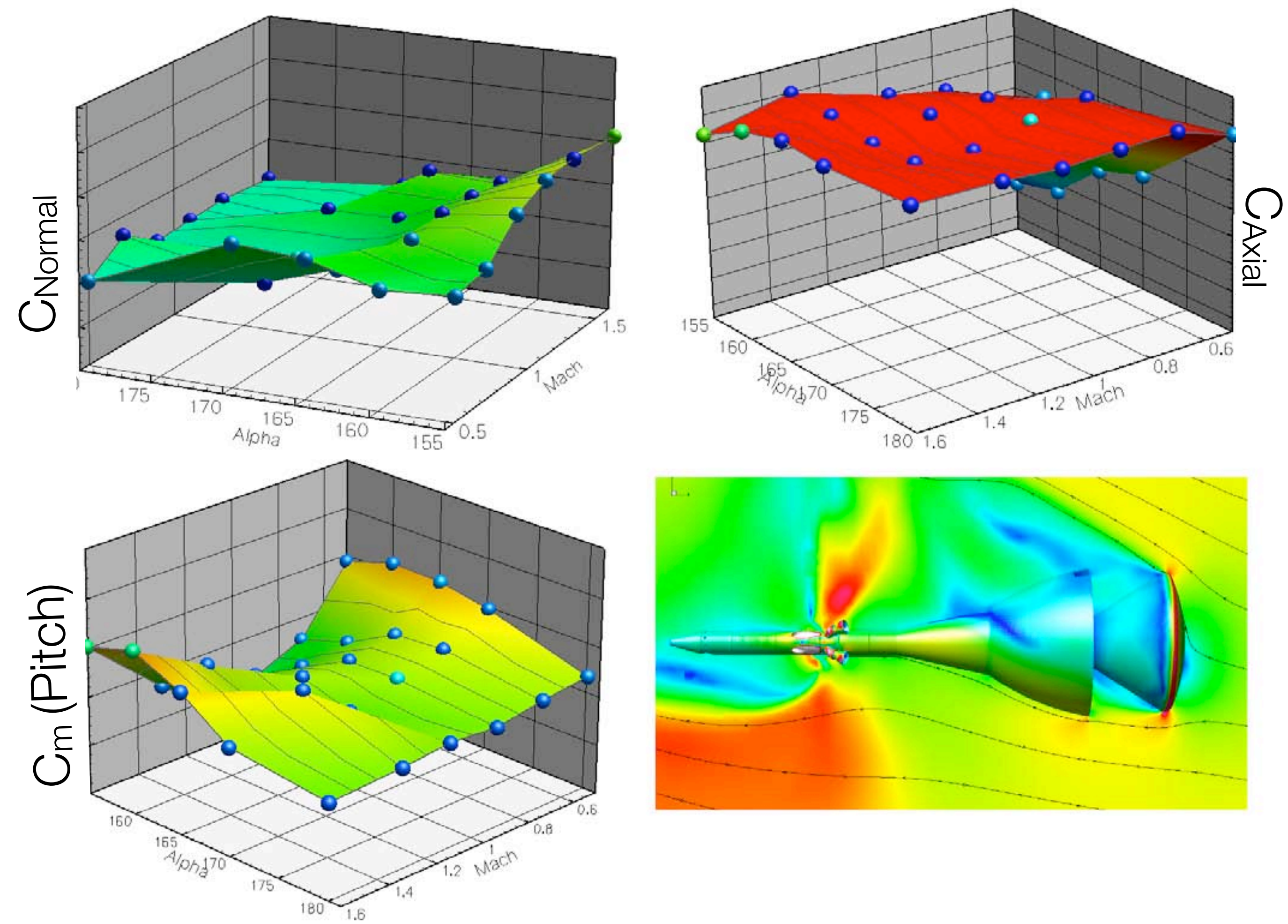
Loads on CM and LAM in proximity

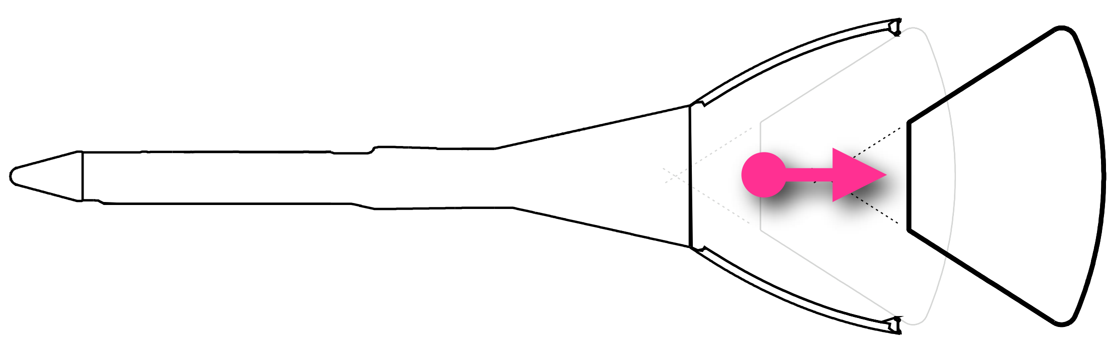
(Δx, 0.0, 0.0, 0°)

Loads on CM



Loads on LAM

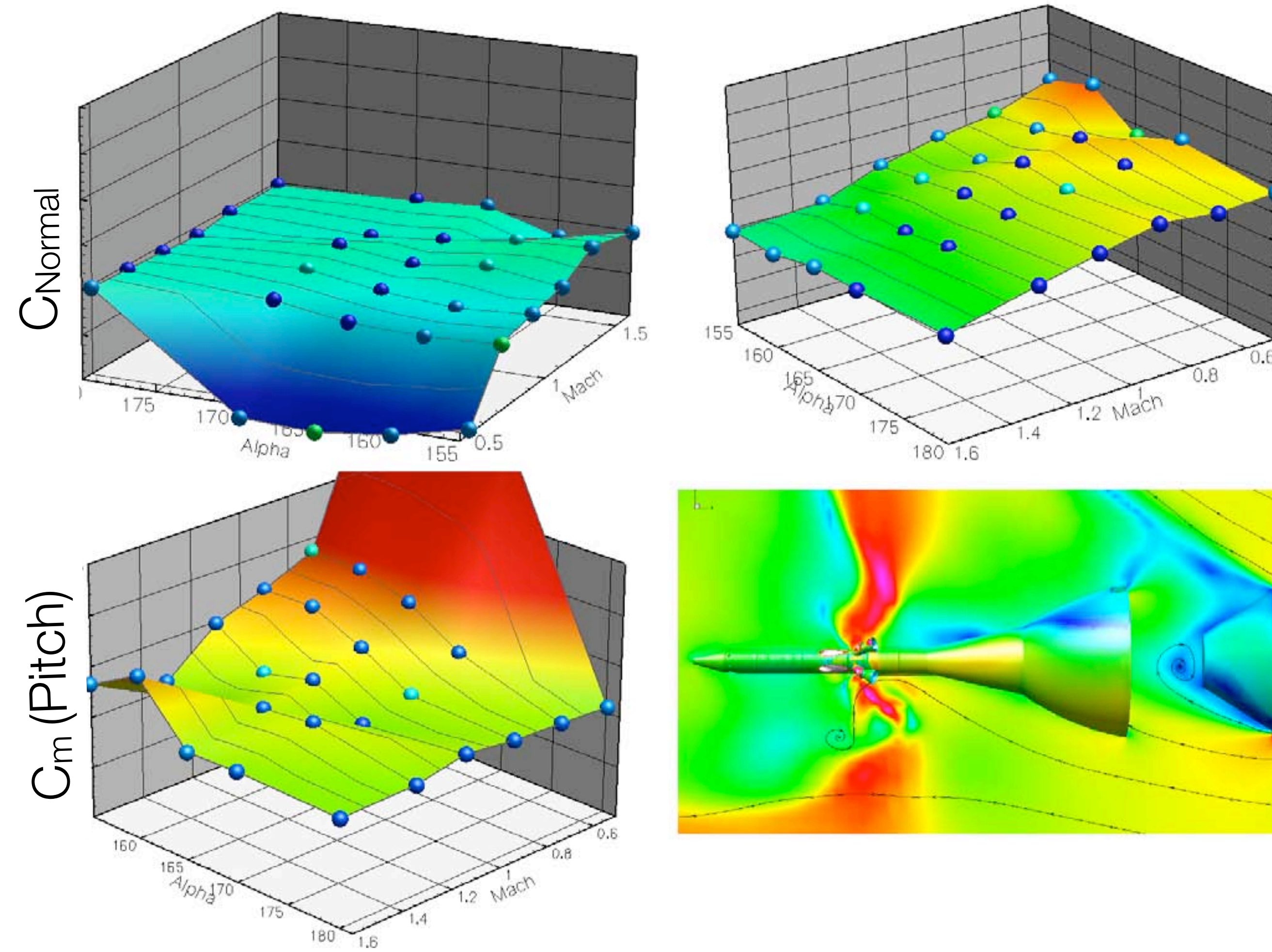




Database Samples

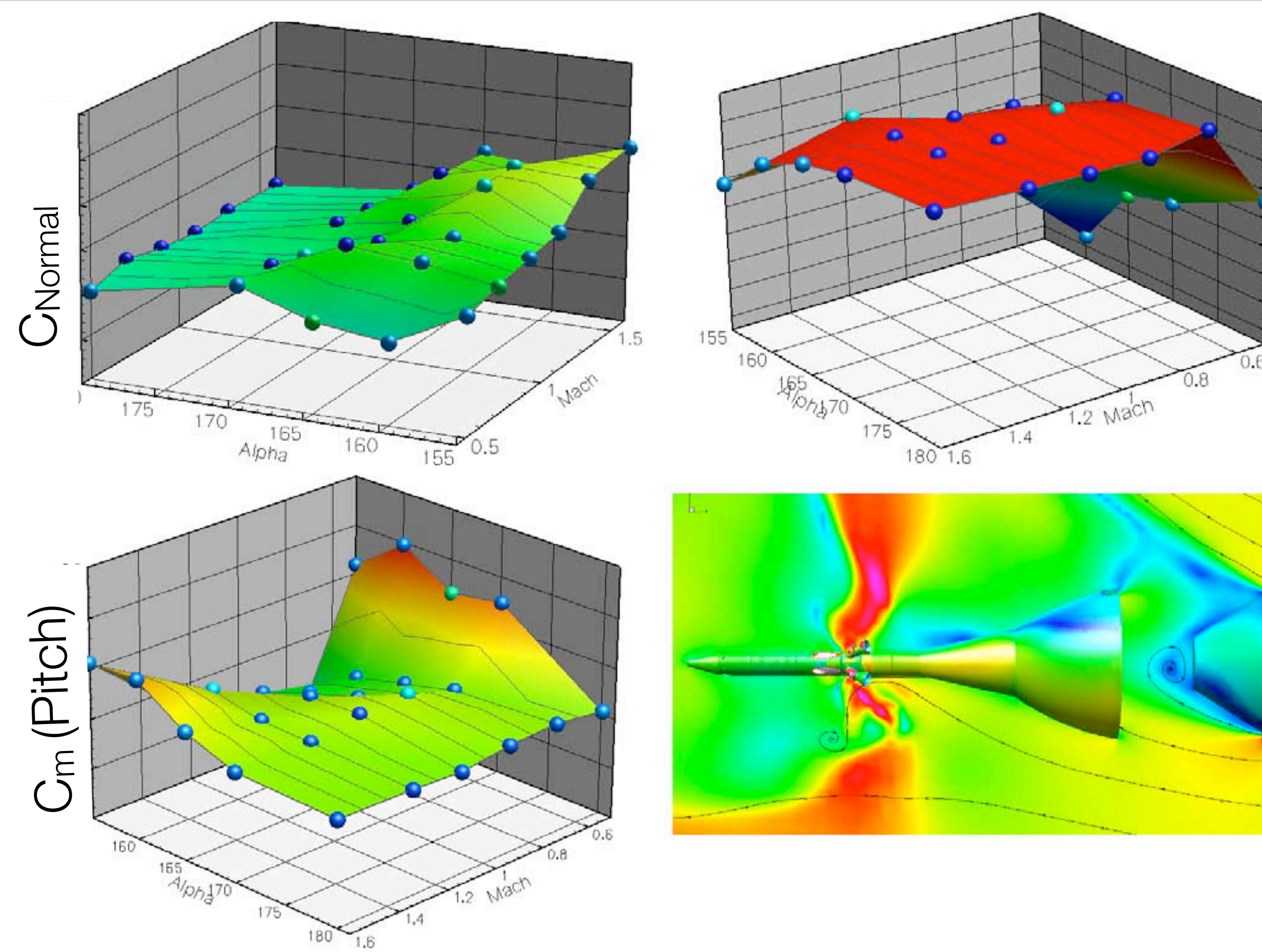
Loads on CM and LAM in proximity

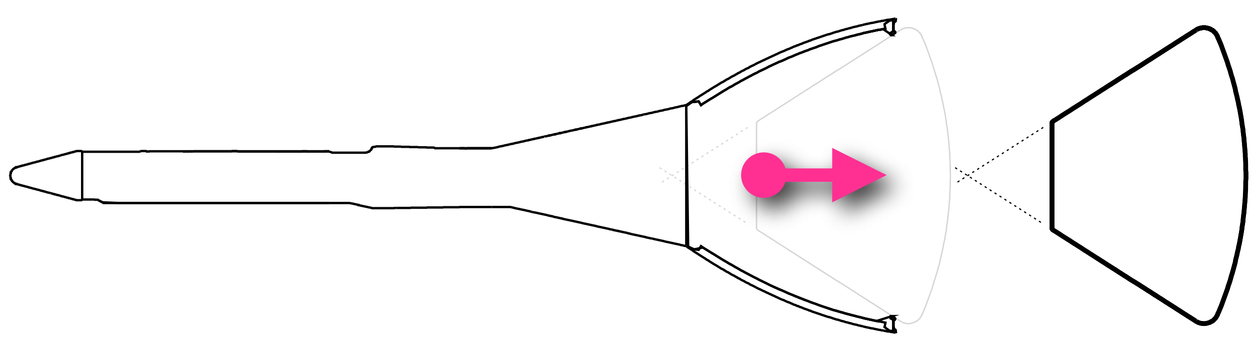
(Δx, 0.0, 0.0, 0°)



Loads on CM

Loads on LAM

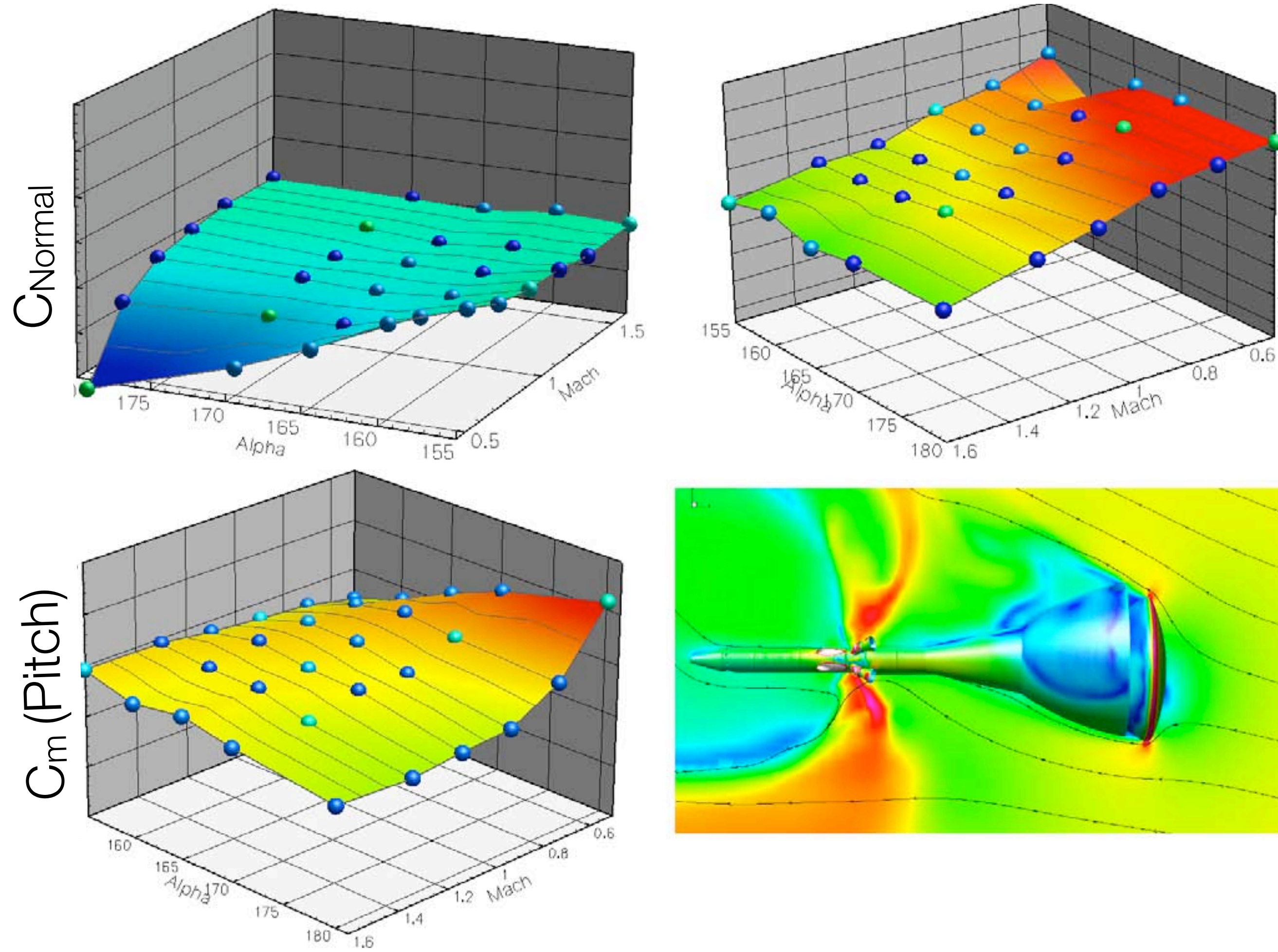




Database Samples

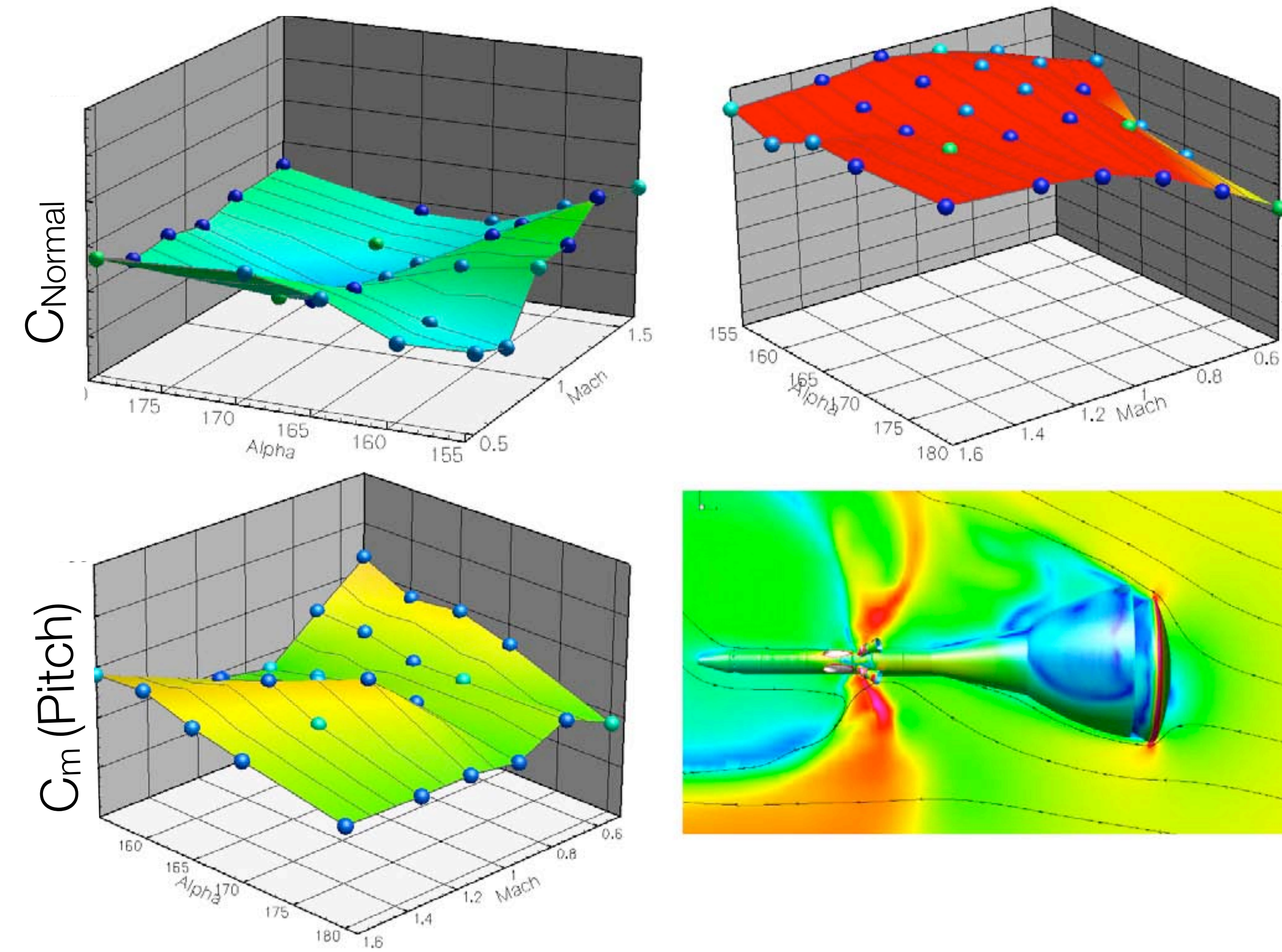
Loads on CM and LAM in proximity

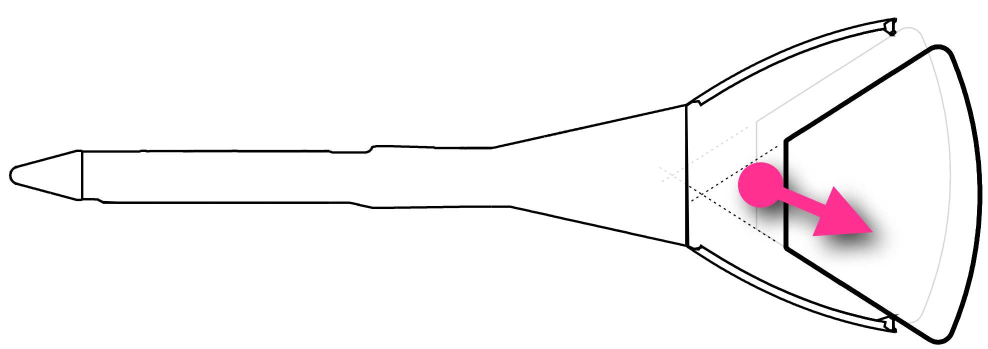
(Δx, 0.0, -Δz, 0°)



Loads on CM

Loads on LAM

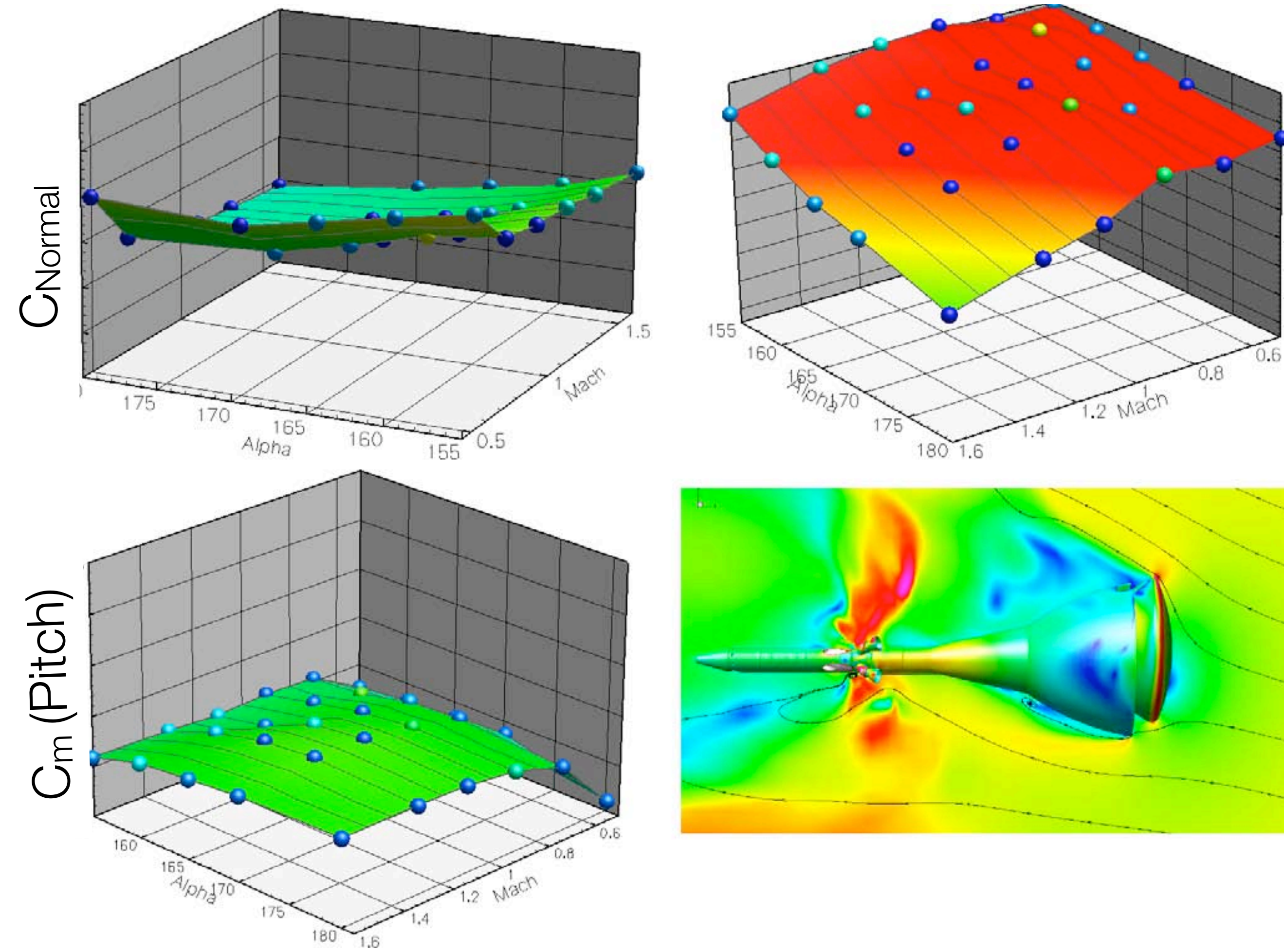




Database Samples

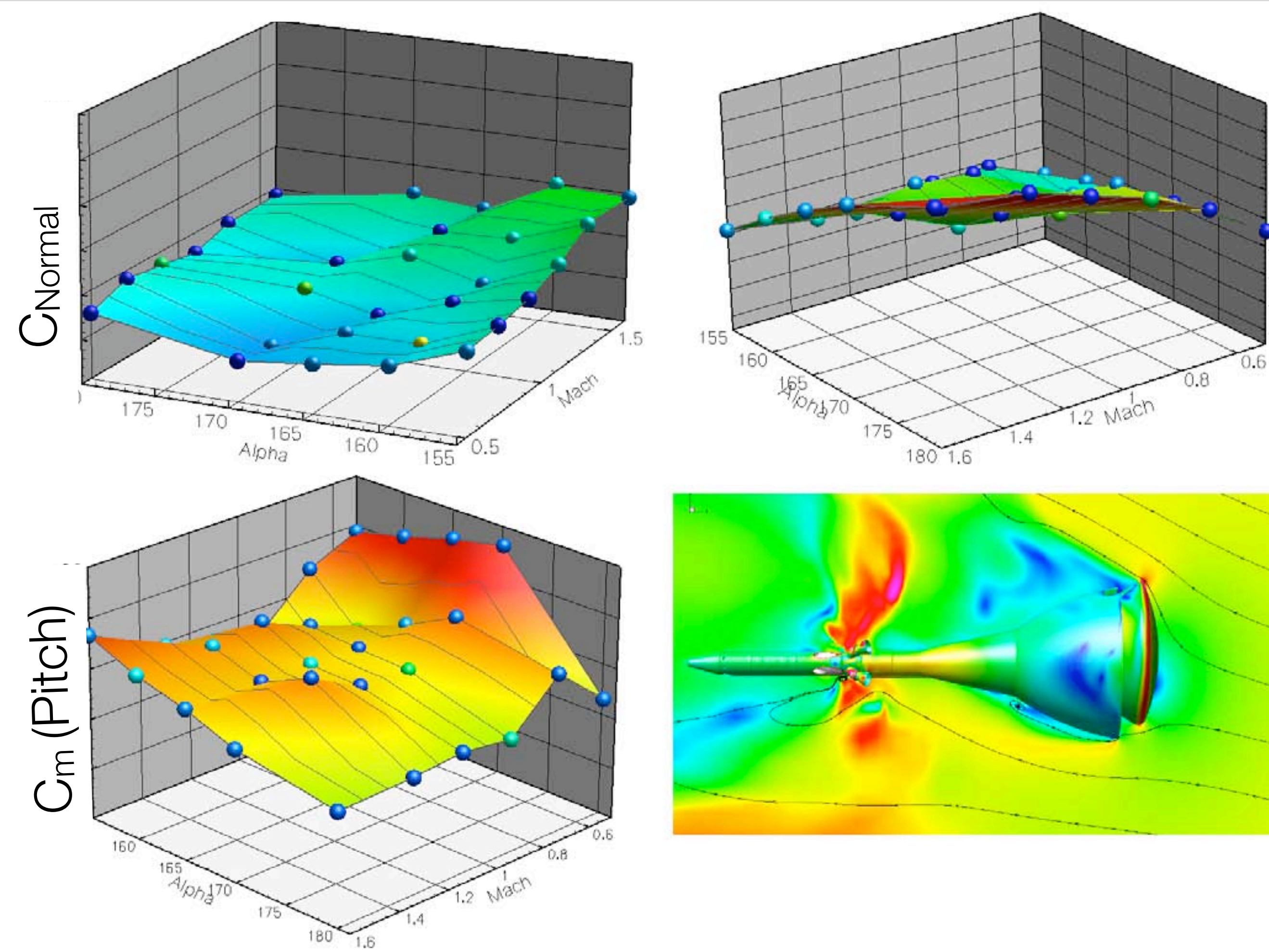
Loads on CM and LAM in proximity

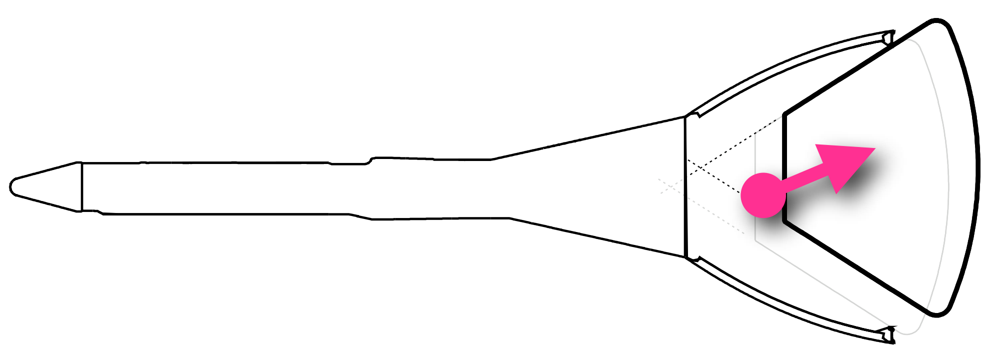
(Δx, 0.0, Δz, 0°)



Loads on CM

Loads on LAM





Summary

Presented a reliable and efficient approach for error estimates and mesh refinement of complex geometry problems

1. Handles complex geometry problems in an automatic fashion
2. Tolerant of coarse initial meshes
3. Behavior of functional, correction, and error estimate provide an indication of errors due to lack-of-convergence in steady simulations

⇨ **It is our best mesh generator … refinement complements and surpasses expert knowledge**

⇨ **Allows users to focus on data validation and analysis instead of mesh generation**

Present and Future Work

- Sonic-boom applications (Mathias Winzter, AIAA 2008-6593)
- Address unsteadiness issues in difficult cases
  - Affordable mesh refinement and error bound for “mildly” unsteady flow
  - Formal unsteady adjoint development
- Control accuracy of objective functions in optimization studies

Acknowledgments

- Marsha Berger, NYU
- Tom Pulliam, NASA Ames
- Scott Murman, NASA Ames
- NASA Ames contract NNA06BC19C